SUSY at JLC

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Abstract

We describe SUSY search and study strategy at JLC. It is pointed out that, from the first SUSY particle alone, we can learn a lot about the SUSY breaking parameters which lead us to the discovery of the next. The experimental procedures to determine the masses and mixings of SUSY particles through the measurements of differential cross sections are explained in detail, where the power of polarized electron beam is stressed. We discuss the implications of the so determined SUSY breaking parameters in relation to the GUT scale physics, taking a sample case.

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1 Introduction

Phenomenological aspects of the low energy supersymmetry are nicely summarized by MURAYAMA[1] together with its theoretical and experimental motivations, and its most concrete prediction, the existence of a light neutral Higgs boson at JLC[2], is discussed in detail by KAWAGOE[3]. The discovery of the lightest neutral Higgs boson alone is, however, not enough to prove the supersymmetry. It is definetely necessary to find *at least* one supersymmetric particle (sparticle). This corresponds to the confirmation of the supersymmetric part of the Lagrangian ($\mathcal{L}_{SUSY}$), which is just the beginning. The supersymmetry breaking (sbreaking) part ($\mathcal{L}_{sbreaking}$), which determines masses and mixings of sparticles is the main dish, since it is believed to be determined by GUT or Planck scale physics. As illustrated in Fig. 1, experimentalists'tasks can, therefore, be summarized as follows: 1) search for a sparticle to prove the existence of $\mathcal{L}_{SUSY}$, and 2) study sparticles and determine masses and mixings of sparticles by measuring differential cross sections.

In this talk, we will first discuss the search and study methods for the first sparticle and show that precision measurements of differential cross sections are indeed possible. Although which sparticle is the first to be discovered is model-dependent, these methods are largely model-independent and can be applied to other sparticles to be found subsequently. In the latter half of this talk, we will demonstrate, taking a sample case, how the discovery of the first sparticle leads to the discovery of the next and what the studies of so found sparticles tell us about the structure of $\mathcal{L}_{sbreaking}$. It should be noted that the polarized electron beam will play an essential role, in the course of the SUSY searches and studies.

2 First Sparticle

In order to get insight into the sparticle spectrum, let us first briefly discuss SUSY parameters (sparameters) and their relation to sparticle masses. To be specific, we will work within the framework of supergravity (SUGRA) models with the "GUT-condition"s, although the search and study methods are largely model-independent and the model assumptions can be tested to a high precision as described later. These models involve, in general, the following parameters: (m_0, M_2, μ, $\tan\beta$), which determine not only the mass spectrum but also the interactions of sparticles[4]. μ is the higgsino mixing mass parameter and $\tan\beta$ is the ratio of the two vacuum expectation values of two Higgs doublets. M_2 is the $SU(2)$ gaugino mass parameter, which is related to the $SU(3)$ and $U(1)$ gaugino mass parameters:

$$\frac{M_1}{\frac{5}{3}\alpha/\cos^2\theta_W} = \frac{M_2}{\alpha/\sin^2\theta_W} = \frac{M_3}{\alpha_s}$$

under the GUT conditions. Numerically, this means

$$M_1 : M_2 : M_3 \simeq 1 : 2 : 7.$$

We expect, therefore, that the lighter chargino, which is a mixture of $SU(2)$ gauginos and charged higgsinos, are much lighter than the $SU(3)$ gauginos (gluinos) (see Fig. 2-a)).

m_0 is the scalar mass parameter, which is common to all the scalar particles in the case of supergravity models (the hidden sector SUSY breaking). Sferminon mass is in general written in the form

$$m_{\tilde{f}} = m_0^2 + G_{\tilde{f}} M_2^2 + D_{\tilde{f}} m_Z^2,$$

where the coefficient of the gauge term ($G_{\tilde{f}}$) is controlled by the size of the gauge group to which the sfermion belongs and the coefficient of the D-term ($D_{\tilde{f}}$) depnds on $\tan\beta$ and is of $O(1)$ or less. Therefore, when $M_2^2 \gg m_Z^2$, the sfermion mass spectrum is largely determined by the gauge term and we can conclude that colored sfermions (squarks) are heavier than uncolored sfermions (sleptons) and right-handed sfermions are lighter than left-handed ones, in general (see Fig. 2-b)). Our first sparticle (FSP) candidates are thus the lighter chargino ($\tilde{\chi}_1^{\pm}$) or the right-handed sleptons ($\tilde{l}_R^{\pm}$).

2.1 Case I: FSP = $\tilde{l}_R^{\pm}$

2.1.1 Slepton Production

The relevant Feynman diagrams for right-handed slepton pair productions are shown in Fig. 3. The s-channel annihilation diagram into a virtual photon or Z is determined solely by quantum numbers of the right-handed slepton ($\tilde{l}_R^{\pm}$) and is common to all of $l = e, \mu, \tau$. This diagram is active for both left-handed and right-handed electron beams. On the other hand, the t-channel neutralino exchange diagrams are present only for $\tilde{e}_R^{\pm}$ and require a right-handed electron beam. Since wino ($\tilde{W}^0$) and higgsino ($\tilde{H}_{1,2}^0$) components of the neutralinos do not couple to $\tilde{e}_R^{\pm}$, only the bino ($\tilde{B}$) components contribute to the t-channel diagrams:

$$t - channel \propto \sum_{i=1}^{4} \frac{|\langle \tilde{\chi}_i^0 | \tilde{B} \rangle|^2}{t - m_{\tilde{\chi}_i^0}^2}.$$

Because of the mass squared appearing in the denominator, the lightest neutralino ($\tilde{\chi}_1^0$), which is assumed to be the lightest sparticle (LSP), gives the dominant contribution. Therefore, when the LSP has a sizable bino component, the t-channel contribution is large, otherwise it is small.

For $\tilde{\mu}_R^{\pm}$, or $\tilde{\tau}_R^{\pm}$, or $\tilde{e}_R^{\pm}$ in the case of left-handed electron beam for which t-channel diagram is absent, the differential cross sections can be written in the form:

$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi} \sigma(\sqrt{s}; m_{\tilde{l}_R}) \cdot \sin^2\theta,$$

where the total cross section has the P-wave threshold factor β^3 and the angular dependence $\sin^2\theta$ characteristic to s-channel pair-production of spinless particles. Fig. 4 plots the production cross sections of smuon pairs as a function of $\sqrt{s}$ for $\mathrm{Pol}_{e^-} = -1, 0$, and $+1$. Notice that the SUSY parameters used here were so chosen that both $\tilde{l}_L^{\pm}$ and $\tilde{l}_R^{\pm}$ can be produced at $\sqrt{s} = 500$ GeV, while $m_{\tilde{l}_R^{\pm}} < M_{\tilde{\chi}_1^{\pm}}$ to be consistent with our assumption.

In the case of right-handed electron beam, the t-channel diagrams modify the angular distribution, depending on the masses and mixings of the neutralinos:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}(\sqrt{s}, \cos\theta; m_{\tilde{e}_R}, \left\langle \tilde{\chi}_i^0 \middle| \tilde{B} \right\rangle, m_{\tilde{\chi}_i^0}).$$

Fig. 5 is a similar plot to Fig. 4 for selectron pair productions, while Figs. 6-a) to -c) plot the differential cross sections. For later use, the cross sections are calculated for four different chirality combinations of the final state selectrons. We can see that, when the electron polarization matchs the final-state slepton chirality, the cross section is enhanced by about a factor of two compared to the unpolarized beam case.

2.1.2 Slepton Decay

Since the production cross sections for slepton pairs are of reasonalble size, if they are produced at all, their detection should be easy when the direct decays into the LSP dominate and the mass difference between the target slepton and the LSP is large. This condition is satisfied when the LSP has a sizable component of the bino state. Figs. 7-a) and -b) show the branching fractions for the direct decays for superpartners of left-handed and right-handed sleptons, respectively, in the m_0-M_2 plane. The figures indicate that the direct mode indeed dominates the $\tilde{l}_R$ decays in most of the parameter space. If FSP $= \tilde{l}_R^{\pm}$, its branching fraction for the direct decay must be 100 %. Notice that in the corresponding parameter region, the direct decay of $\tilde{l}_L^{\pm} \rightarrow l^{\pm} + \tilde{\chi}_1^0$ also has a sizable branching fraction. Figs. 8-a) and -b) are the corresponding contours for the mass differences. Almost everywhere in the parameter space, the mass differences are large enough for detection. The signal of slepton pair productions is, therefore, an acoplanar lepton-pair.

2.1.3 Slepton Search

Since selectron pairs have a larger cross section than smuons, selectron search is easier than that of smuons. Fig. 9-a) is an example of acoplanarity distribution for smuon pair productions, after the accumulation of 10 fb^{-1} (20 days) at $\sqrt{s} = 350$ GeV. The background is predominantly W pairs which are produced from both s- and t-channel diagrams. The s-channel diagram for the W-pair production contains the triple-gauge-boson vertices originating from the $W^+W^-W^0$ vertex, where the W^0 component of $SU(2)$ gauge bosons couples only to left-handed electrons. In the symmetry limit, therefore, the s-channel diagram is absent for a right-handed electron beam, which, at the same time, kills the t-channel diagram involving neutrino exchanges. The right-handed electron beam further improves the signal-to-background ratio by doubling the signal cross section and provides a virtually background-free sample with a typical detection efficiency $\epsilon \gtrsim 50$ % (see Fig. 9-b)).

2.1.4 Mass Determination

Once a slepton is discovered, we can determine the masses of the slepton and the LSP from the energy spectrum of the final state leptons. Fig. 10-a) is the energy distribution of muons from smuon decays for an integrated luminosity of 18 fb^{-1} with a right-handed electron beam. Though the distribution is a little bit different from the rectangular shape expected for spinless particles due, primarily, to selection cuts, the lower and the higher edges are sharp enough. These end points of the energy spectrum determine $m_{\tilde{\mu}}$ and $M_{\tilde{\chi}_1^0}$. Fig. 10-b) shows the contours obtained from the fit to the Monte Carlo data. We can determine the smuon and the LSP masses with statistical errors of 1.4 GeV and 1.0 GeV, respectively.

2.1.5 Differential Cross Section Measurement

In spite of the two LSP's missing in the final state, we can solve the kinematics, using the slepton and the LSP masses determined from the lepton energy spectrum and ignoring initial state radiation and beamstrahlung. Fig. 11-a) is the $\cos\theta$ distribution of $\tilde{\mu}_R^-$ with respect to the electron beam axis. The points with error bars are reconstructed Monte Carlo data corresponding to 5k generated events which is about 90 fb^{-1} equivalent. Notice that there are always two solutions both of which are plotted in the figure. The comparison with the generated distribution for the selected sample tells us that the wrong solution is almost flat and has no particular structure. After the backgound subtraction, we obtain Fig. 11-b) which is compared with the generated distribution without selection cuts. The distribution has a $\sin^2\theta$ distribution and confirms the s-channel pair production of spinless particles. Figs. 12-a) and -b) are similar plots for $\tilde{e}_R^-$, where the angular distribution is affected by the t-channel neutralino exchange diagrams. The slight discrepancy near $\cos\theta = 1$ in Fig. 12-b) is due to the selection cuts.

2.2 Case II: FSP = $\tilde{\chi}_1^{\pm}$

2.2.1 Chargino Production

Fig. 13 shows the Feynman diagrams for lighter chargino pair productions. Unlike the slepton case, the s-channel diagram now depends on the SUSY parameters through the wino-higgsino mixing:

$$\begin{pmatrix} \tilde{\chi}_{1L/R}^- \\ \tilde{\chi}_{2L/R}^- \end{pmatrix} = \begin{pmatrix} \cos\phi_{L/R} & \sin\phi_{L/R} \\ -\sin\phi_{L/R} & \cos\phi_{L/R} \end{pmatrix} \begin{pmatrix} \tilde{W}_{L/R}^- \\ \tilde{H}_{1L/2R}^- \end{pmatrix},$$

where the mixing angles $\phi_{L/R}$ are determined by μ, M_2, and $\tan\beta$. The t-channel diagram involves the electron sneutrino ($\tilde{\nu}_e$) echange and, therefore, vanishes for a right-handed electron beam. Since the Yukawa coupling of electron is negligible, the higgsino components do not contribute to this diagram:

$$t - channel \propto \frac{|\langle \tilde{W}^- | \tilde{\chi}_1^- \rangle|^2}{t - m_{\tilde{\nu}_e}^2}.$$

The effect of the t-channel diagram is large when $m_{\tilde{\nu}_e}$ is small and the wino component is large. The differential cross section depends on the SUSY parameters, through the masses and mixings:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}(\sqrt{s}, \cos\theta; m_{\tilde{\chi}_1^\pm}, m_{\tilde{\nu}_e}, \phi_L, \phi_R).$$

Fig. 14-a) compares the $\sqrt{s}$ dependence of the production cross section for the following three typical cases: pure winos, equal mixtures of wino and higgsino, and pure higgsinos when the sneutrino mass is kept constant at $m_{\tilde{\nu}} = 1000$ GeV. For this sneutrino mass, the contribution of the t-channel diagram is negligible at $\sqrt{s} < 500$ GeV and the cross section shows the S-wave threshold factor proportional to β. Fig. 14-b) is the same figure for $m_{\tilde{\nu}} = 250$ GeV, where we can see that the t-channel sneutrino exchange diagram modifies the threshold shape as well as its magnitude.

The beam polarization dependence of the differential cross section is shown in Figs. 15-a) and -b). We can see that the shape of the anglular distribution is very sensitive to the composition of the chargino, when the electron beam is unpolarized. In the previous section, we have shown that the right-handed electron beam kills the W-pair background. Since wino is the superpartner of the W boson, the right-handed beam also eliminates the contribution from the wino component and alows us to study the higgsino components separately.

2.2.2 Chargino Decay

Under our assumption that the lighter chargino is the lightest charged SUSY particle, $\tilde{\chi}_1^\pm$ becomes the next to the lightest SUSY particle. Here we note that, when $\Delta m \equiv M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0} > M_W$, the branching fractin for the $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W$ mode is essentially 100 %, unless the higgsino component is negligible. As long as the lighter chargino has a sizable higgsino component, its decay is dominated by a "beta-decay", even if $\Delta m < m_W$. This is because the $\tilde{\chi}_1^- \to f\tilde{f}^*$ modes are strongly suppressed by the sfermion propagator, in the case where the sfermions are heavier than the lighter chargino and thus are much heavier than the W boson. Notice that in the parameter space of our interest: $m_0 \gtrsim 200$ GeV, $\mu \lesssim 1$ TeV, and $M_2 \lesssim 200$ GeV, the branching ratio for the hadronic mode always exceeds ~ 50 %, even if the lighter chargino is wino-rich. On the other hand, the branching ratio for the leptonic mode is at least 33 % which increases with the fraction of the wino component. The measurement of the leptonic branching ratio provides additional information on the composition of the chargino.

Fig. 16 shows this mass difference in the μ-M_2 plane. In the region where $M_2 \ll \mu$, the lighter chargino is wino-rich and the LSP is essentially a bino state and, therefore, the mass difference is large. In this case, the detection of the chargino is easy, though we cannot use the right-handed beam to suppress the W-pair background. On the other hand, the $M_2 \gg \mu$ region corresponds to a higgsino-rich chargino and the mass difference might be small. The detection of such a chargino is difficult, but the right-handed electron beam should be very helpful.

2.2.3 Chargino Search

When the decay into a real $W(\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-)$ is kinematically allowed, the best signal is an acoplanar pair of W's reconstructed from a four-jet final state, since the potentially most serious background from $e^+e^- \to W^+W^-$ is absent and the remaining background from $e^+e^- \to W^+W^-Z$ has only a small cross section. In this case, the detection of the chargino is straightforward.

In the following, therefore, we will focus our attention on the case where the two-body decay is kinematically forbidden. Considering the background from W-pair productions and two-photon processes, the best channel, in this case, is again the four-jet mode. However, we will try to use the final state where one of the chargino decays hadronically: $\tilde{\chi}_1^- \to q\bar{q}\tilde{\chi}_1^0$, while the other decays leptonically: $\tilde{\chi}_1^- \to l^-\bar{\nu}\tilde{\chi}_1^0$, since the combinatorial ambiguity is absent in this mode and, therefore, the determinations of the chargino and the LSP masses are easy. In addition, if $\Delta m < m_W$, we cannot solve the kinematics to reconstruct the chargino production angle. In this case, we need to use the decay lepton angular distribution anyway.

Notice that the background from W-pair productions can be effectively removed by requiring that the invariant mass of the two-jet system and that of the lepton and the reconstructed neutrino are inconsistent with the W-pair hypothesis, while the two-photon processes can be eliminated by requiring an energetic isolated lepton. The remaining W-pair contamination can be further reduced by cuts on the polar angles of the isolated lepton and the two-jet system and a cut on the acoplanarity.

The signature to look for is then two jets and a single energetic isolated lepton with a large missing transverse momentum or a large acoplanarity, for which the W-pair hypothesis is disfavored, provided that the mass difference $\Delta m \equiv M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}$ is sufficiently large to produce the energetic isolated lepton. As already shown in Fig. 16, this mass difference is large enough for detection in most of the parameter space. The remaining question is whether this is large enough for the separation from the potential background processes such as two-photon processes or W-pair productions.

Fig. 17 is an example of the acoplanarity distribution of the two-jet+lepton final states from the chargino decays for an integrated luminosity of 10 fb^{-1} (20 days) at $\sqrt{s} = 500$ GeV. Also shown is the W-pair background (open histogram). Both the signal and the background are with all the cuts except for the one on the acoplanarity. The cut at $\theta_{acop} = 30^o$ provides a virtually background-free sample of the chargino pairs with a reasonable efficiency $\epsilon \gtrsim 13$ %, including the branching fraction of 30 %.

2.2.4 Mass Determination

When the chargino signal is detected, the next task is the determination of the chargino and the LSP masses. For this, we look at the energy distribution of the two-jet systems from the chargino decays which is shown in Fig. 18. Notice that, unlike the slepton case, the distribution depends on the structure of the decay vertex. Nevertheless, the end points of the distribution are determined by the chargino and the LSP masses. Therefore the shape of the distribution may provide us with additional information on the SUSY

parameters.

The expected statistical errors on $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_1^0}$ are 3.2 GeV and 2.0 GeV, respectively, when we fit the distribution to a polynomial.

The LSP mass together with the lighter chargino mass fixes two out of the three parameters (M_2, μ, and $\tan\beta$) in the chargino-neutralino mass matrices, leaving only one parameter undetermined. If the LSP is lighter than the observed chargino by a factor of $(5/3)\tan^2\theta_W$, then it strongly suggests that they are almost pure wino and bino states. On the other hand, if the mass ratio of the LSP and the chargino is different from $(5/3)\tan^2\theta_W$, it signals a substantial mixing with higgsino states, indicating a light higgsino. For instance, a 10% shift requires the higgsinos to be lighter than $\sim 10 m_{\tilde{\chi}^0}$.

2.2.5 Differential Cross Section Measurement

The differential cross section gives us yet another handle to determine the SUSY parameters. Fig. 19 shows the corresponding polar angle distribution of the l^-'s from the $\tilde{\chi}_1^-$ decays which is compared with the theoretical predictions for different sets of the SUSY parameters. For completeness, let us consider the $\Delta m > m_W$ case. This time we can reconstruct the chargino production angle as we did for the sleptons, using the 4-jet mode. Fig.20-a) shows the reconstucted production angle distribution, where both of the two solutions are plotted. Again the wrong solutions make an almost flat background. After the background subtraction, we obtain Fig. 20-b), where the histogram is the scaled generated distribution without selectoin cuts. Though the problem of the jet-charge determination remains to be solved (we might use charme ID or Q_{jet}), the differential cross section measurement seems feasible also for the lighter chargino.

3 SUSY Search and Study Scenario

As described in the previous section, the first sparticle alone can tell us a lot about the sbreaking parameters through the mass and differential cross section measuremnts. The information on the sbreaking parameters will lead us to discoveries of series of sparticles. The SUSY mass spectrum will put strong constraints on the supergravity parameters, especially on M_2 and m_0. In a lucky situation, we may even be able to determine all the sbreaking parameters in the minimal supergravity, (M_2, m_0, μ, $\tan\beta$, A, B). It should be emphasized that we can not only determine the sbreaking parameters but also test if the SUSY mass spectrum is indeed determined by this small set of parameters. In this way, we can explore physics at the Planck scale, since the nature of the sbreaking mechanism is believed to come from the supergravity interactions.

We will sketch below the SUSY search and study scenario for a sample case where the right-handed charged slepton is the FSP: $(m_0, \mu, M_2, \tan\beta) = (70\ \text{GeV}, 400\ \text{GeV}, 250\ \text{GeV}, +2)$. The right-handed charged slepton masses are expected to be degenerate among generations. The right-handed selectron $\tilde{e}_R$ has larger production cross section than smu $\tilde{\mu}_R$ or stau $\tilde{\tau}_R$ due to the t-channel neutralino-exchange diagram. After first observations of highly acoplanar electron pair events, we will use the right-handed electron beam to

suppress the W-pair background. Then the detection of all three right-handed charged sleptons ($\tilde{e}_R$, $\tilde{\mu}_R$, and $\tilde{\tau}_R$) is relatively easy. Using the energy distributions of final-state charged leptons, we can measure the masses of sleptons and the LSP at the percent level. Already at this point, we can check one of the most important assumptions, the hidden-sector SUSY breaking, which predicts the slepton mass degeneracy among generations. The universality of the masses of $\tilde{e}_R$, $\tilde{\mu}_R$, and $\tilde{\tau}_R$ will strongly support the hidden-sector scenario of sbreaking (see Fig. 21).

The t-channel neutralino-exchange diagrams enhance the production cross section for selectron pairs. Since only the bino component contributes to the enhancement, the selectron production cross section essentially measures the bino mass M_1. Since the LSP mass $m_{\rm LSP}$ is already fixed, we can test whether the LSP is bino-like or higgsino-like, by comparing M_1 and $m_{\rm LSP}$. If the cross section is consistent with the t-channel exchange of the LSP, then it is almost a pure bino. On the other hand, if the cross section roughly equals that of smus or staus, then the LSP is almost a pure higgsino. Otherwise, the LSP is a mixture. In this case, the mass of the LSP and the cross section put two constraints on the neutralino-chargino mass parameters (M_2, μ, $\tan\beta$). The differential cross section further constrains these parameters. In any case, it is remarkable that we can set an upperbound on the mass of the lighter chargino from $m_{\rm LSP}$ alone. Fig. 22 shows the upper limit on the lighter chargino mass as a function of the LSP mass. For the LSP mass greater than 30 GeV, the lighter chargino mass never exceeds twice the LSP mass. For a higgsino-like LSP, the lighter chargino (an almost-pure charged higgsino) lies just above the LSP. For a bino-like LSP, the lighter chargino (an almost-pure charged wino) is roughly twice as heavy as the LSP.

The upperbound on the lighter chargino mass obtained from $m_{\rm LSP}$ sets the energy for the chargino search. We have shown that the lighter chargino mainly decays into LSP+W, whose detection is easy. Even in a small region of the parameter space where it decays into three-body final states, we can discover the chargino as far as it is heavier than the LSP by $\Delta m \gtrsim O(5)$ GeV.

If the gaugino-higgsino mixing is large (*i.e.*, $M_2 \simeq \mu$) the measurements of $m_{\tilde{\chi}^\pm}$, and production cross sections both for right-handed ($\sigma_R(\tilde{\chi}^\pm)$) and left-handed ($\sigma_L(\tilde{\chi}^\pm)$) beams, together with $m_{\rm LSP}$, fix all the three parameters of the neutralino-chargino sector (M_2, μ, $\tan\beta$) under the assumption of the GUT-condition $M_1/M_2 = \alpha_1/\alpha_2$. In this case, the mass of the heavier chargino can be predicted, and should lie near above the lighter one. Its discovery at the predicted mass will confirm the GUT-condition here assumed. In our example case of $M_2 < \mu$, the lighter chargino is almost a pure charged wino. The measurements are, then, not very sensitive to μ and $\tan\beta$. Even in this case, however, we can test the GUT-condition. The bino mass M_1 is roughly $m_{\rm LSP}$, and the wino mass M_2 is roughly the chargino mass $m_{\tilde{\chi}^\pm}$. Fig. 23 shows the $\Delta\chi^2 = 1$ contour in the (M_1, M_2) plane, which clearly demonstrates the possibility of a precision test of the SUSY-GUT assumption. The measurement of the differential cross section provides additional constraints on the sbreaking parameters.

There is another information we can obtain from the study of the lighter chargino. The cross section from the left-handed electron beam $\sigma_L(\tilde{\chi}^\pm)$ carries the contribution from the t-channel sneutrino ($\tilde{\nu}_L$) exchange. The dependence of σ_L on $m_{\tilde{\nu}_L}$ is shown in Fig. 24.

We can determine the sneutrino mass with a precision of about $5-20$ GeV.

$m_{\tilde{\nu}_L}$ is related to the mass of the left-handed charged slepton $m_{\tilde{l}_L}$ in a model-independent way,

$$m^2_{\tilde{\nu}_L} \leq m^2_{\tilde{l}_L} = m^2_{\tilde{\nu}_L} + (1-\sin^2\theta_W)m_Z^2|\cos(2\beta)| \leq m^2_{\tilde{\nu}_L} + (1-\sin^2\theta_W)m_Z^2, \qquad (1)$$

for $\tan\beta \geq 1$. This inequality allows us to set the next energy.

The left-handed charged slepton will be searched first in the process $e^-_R e^+ \to \tilde{e}^-_R \tilde{e}^+_L$, from the t-channel bino-exchange. The discovery of the left-handed selectron at the predicted mass confirms the SUSY-nature of the sleptons. If lucky, it is even possible to determine $\tan\beta$ from the above formula. The important implication of the measured $m_{\tilde{l}_L}$ is that we can check the universal scalar mass hypothesis in the hidden-sector scenario of the SUSY-breaking. The SUSY-GUT alone predicts

$$m^2_{\tilde{l}_L} = m_5^2 - \left(\frac{3}{2}(\alpha_2^2-\alpha_0^2) + \frac{1}{22}(\alpha_1^2-\alpha_0^2)\right)\frac{M_2^2}{\alpha_2^2} - \frac{1}{2}m_Z^2\cos 2\beta(1-2\sin^2\theta_W), \qquad (2)$$

$$m^2_{\tilde{\nu}_L} = m_5^2 - \left(\frac{3}{2}(\alpha_2^2-\alpha_0^2) + \frac{1}{22}(\alpha_1^2-\alpha_0^2)\right)\frac{M_2^2}{\alpha_2^2} - \frac{1}{2}m_Z^2\cos 2\beta, \qquad (3)$$

$$m^2_{\tilde{l}_R} = m_{10}^2 - \frac{2}{11}(\alpha_1^2-\alpha_0^2)\frac{M_2^2}{\alpha_2^2} - m_Z^2\cos 2\beta\sin^2\theta_W, \qquad (4)$$

where m_5 and m_{10} are masses common for the **5**- and **10**-dimensional representations. The universal scalar mass hypothesis implies $m_5 \simeq m_{10}$. Then the difference between left-handed and right-handed charged slepton masses is determined solely by the gaugino mass

$$m^2_{\tilde{l}_L} - m^2_{\tilde{l}_R} \simeq \left(\frac{3}{2}(\alpha_0^2-\alpha_2^2) - \frac{5}{22}(\alpha_0^2-\alpha_1^2)\right)\frac{M_2^2}{\alpha_2^2}. \qquad (5)$$

The expected $\Delta\chi^2 = 1$ contour in the plane $m^2_{\tilde{l}_L} - m^2_{\tilde{l}_R}$ versus M_2^2 is shown in Fig. 25, with the prediction of the universal scalar mass hypothesis. Thus the measurement of $m_{\tilde{l}_L}$ will put a strong constraint on the supergravity model building.

Finally, the discovery of other left-handed charged sleptons $\tilde{\mu}_L$ and $\tilde{\tau}_L$ will again put constraints on the hidden-sector scenario of SUSY-breaking which predicts the mass degeneracy among generations. Furthermore, the t-channel neutral wino ($\tilde{W}^0$) exchange diagram exists for the $\tilde{e}_L$-pair production from the left-handed electron beam, which serves as a cross-check of the measured SUSY parameters. At this point, we can even test the radiative breaking scenario, if the pseudo-scalar Higgs mass (m_A) is known.

Though we have concentrated on the case where the right-handed charged slepton is the first to be discovered at JLC, the strategy is similar for the case where the lighter chargino is the first. The study of the chargino will determine the three parameters of the neutrino-chargino sector, and also the sneutrino mass can be measured from $\sigma_L(\tilde{\chi}^\pm)$. Then we obtain upperbound on $m_{\tilde{l}_L}$, and the same analysis as above can be carried out.

4 Summary and Conclusion

SUSY search at JLC is easy and we can cover sparticle masses roughly up to the kinematical limit. With the help of the polarized electron beam, we can get a very clean sample of sparticle-pair events even for smuons which have a relatively small production cross section compared to the W-pair background. Using this clean sample, we can carry out precision measuremnts of the masses and differential cross sections and learn a lot about the sbreaking parameters from the first sparticle alone. The discovery of the first sparticle thus leads us to the subsequent discoveries of other sparticles. The mass and cross section measurements of these sparticles will not only determine the sbreaking parameters, but also allows us to test the key assumptions of the supergravity models such as GUT-conditions, the hidden-sector SUSY-breaking (universal scalar mass), and possibly the radiative breaking of the electroweak symmetry. Since the structure of the sbreaking Lagrangian is believed to be determined by supergravity interactions, we can make a first realistic step towards GUT/Planck-scale physics. All of these crucially depends on the cleanness of the e^+e^- linear collider and the availability of the highly polarized electron beam. In conclusion, we may say that, once the first sparticle is found, JLC will be an ideal "S-machine" to do "S-physics".

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