Probing the s generation spectrum
in chargino decays

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Some mechanisms of supersymmetry breaking result in splitting of the third generation sfermions from the other sfermions. We show that the three-body decay branching ratio of the lighter chargino gives a sensitive probe of the sfermion mass spectrum if the chargino has a large gaugino component.
If supersymmetry is the Nature’s choice for the solution of the naturalness problem, a plethora of new particles should exist just above the weak scale. Each known particle is accompanied by its superpartner. The pattern of the sparticle mass spectrum reflects the mechanism of supersymmetry breaking. One of the interest lies in the generation structure of the sfermion masses. Although the neutral kaon system gives a strong constraint that the first and second generation squarks should be nearly degenerate or very massive, the third generation sfermions are much less constrained. Indeed, in the supergravity scenario of supersymmetry breaking, mass splitting of the third-generation and the other sfermions results from the renormalization group evolution of the masses between the unification scale and the weak scale, even if the sfermions have equal masses at the unification scale. This splitting is due to the effect of the large Yukawa coupling of the top. The bottom and tau sectors are also affected if the parameter tan\( \beta \) (the ratio of the two higgs vacuum expectation values) is large. There are also arguments that first and second generation sfermions can be as heavy as 10 TeV without conflicting the naturalness problem, while the third generation sfermions have to be rather light.

Electron-positron colliders are best machines to search for colorless superparticles. Much effort has been devoted to supersymmetry searches at LEP, each time its energy is raised. Linear colliders with higher energies are in the stage of planning, which would extend the scope of the searches. If superparticle mass spectrum is widely distributed, we can hardly expect that all superparticles are found at one experiment. Rather, first discovery would be confined to one or some of the lighter superparticles, heavier ones being beyond the reach of the machine. It would be desirable if one can extract some information on the heavier superparticles by studying the properties of the lighter ones.

There are two possibilities of doing this. One is to exploit the supersymmetric relations between couplings such as the equality of gauge couplings and gaugino couplings. These relations receive corrections from supersymmetry breaking which depend logarithmically on heavy superparticle masses. This effect (sometimes called the ‘super-oblique’ correction) has been studied recently by several groups.

Another possibility is to look for the effect of virtual sparticle exchanges. Unlike the superoblique corrections, this effect vanishes if the superparticle mass is large (the decoupling theorem). We find, however, there are cases in which this effect is quantitatively important.
In this paper we present a test case of the latter possibility. One of the likely first superparticles is the (lighter) chargino, which generally is a mixture of the wino and the charged higgsino. Charginos can be produced in pairs in $e^+e^-$ collisions. If the two body decay channels such as neutralino + W are not open, the chargino decays to a neutralino and a fermion-antifermion pair. The three-body decay is important in a substantial region of the parameter space. In this region, the branching ratio of the modes depends on the masses of the intermediate sfermions. The ratio of leptonic and hadronic decay rate has been discussed by Oshimo and Kizukuri [10]. We concentrate on the leptonic decays in the present paper and study the dependence of the branching ratio on the slepton masses, allowing unequal selectron/smuon and stau masses. The phenomenological consequences of light staus have been examined in the framework of the minimal supergravity scenario by Baer et al. [11].

Determination of supersymmetry parameters using chargino pair production has been studied by several groups [12]–[15]. It was demonstrated in these works that the chargino-neutralino sector parameters $M_2$, $\mu$, $\tan \beta$ as well as the electron sneutrino mass can be deduced from chargino production cross sections and various distributions in $e^+e^-$ collisions. In this work, we assume that these parameters are well determined and concentrate on the effect of slepton masses. Feng and Strassler [15] and one of us [9] have also examined the ratio of leptonic and hadronic branching fractions.

The chargino-neutralino sector in the minimal supersymmetric standard model can be described by three unknown parameters, if one assumes the grand unification of the gaugino masses. They are the SU(2) gaugino mass $M_2$, the higgsino mass parameter $\mu$, and $\tan \beta$. The hypercharge U(1) gaugino mass $M_1$ is given by $M_1 = \frac{5}{3}M_2\tan^2\theta_W \simeq 0.5M_2$.

We fix the mass of the lighter chargino $\tilde{\chi}_1^\pm$ (hereafter the chargino) as one of the parameters. The remaining two may be chosen as $M_2/\mu$ and $\tan \beta$. The composition of $\tilde{\chi}_1^-$ is mainly determined by $M_2/\mu$. It is mostly wino if $M_2/\mu \ll 1$ (gaugino region) and mostly higgsino $\tilde{\chi}_1^\pm \simeq \tilde{H}_1^L + \tilde{H}_2^R$ if $M_2/\mu \gg 1$ (Higgsino region). In the region $M_2/\mu \sim 1$, $\tilde{\chi}_1^\pm$ contains substantial components of the both. The mixing angles have slight dependence on $\tan \beta$ and its sign (or equivalently the sign of $\mu$).

In the gaugino region, the lightest neutralino $\tilde{\chi}_1^0$ is mostly the bino (hypercharge gaugino) and its mass is about a half of the chargino mass. The second lightest neutralino $\tilde{\chi}_2^0$ is mostly the neutral wino (an SU(2) gaugino) and is nearly degenerate with the chargino. In the higgsino region, the light-
est neutralino is a higgsino state which almost degenerates with (but lighter than) the chargino. The second lightest neutralino, which is also a higgsino state, lies just above the chargino.

Now we turn to the decay modes of $\tilde{\chi}^-_{1}$. The final state must contain one superparticle in the minimal framework with $R$ parity conservation. We are interested in the case that the sfermions are heavier than the chargino and the decays $\tilde{\chi}^-_{1} \rightarrow f + \bar{f}$ are not allowed. If the mass difference between $\tilde{\chi}^-_{1}$ and $\tilde{\chi}^0_{1}$ is large enough, the chargino decays by emitting a $W$ boson $\tilde{\chi}^-_{1} \rightarrow \tilde{\chi}^0_{1} + W^-$ or by emitting a charged Higgs boson (which is usually heavier than the $W$). If these decays are kinematically forbidden, the main decay modes are

$$
\tilde{\chi}^-_{1} \rightarrow \tilde{\chi}^0_{1} + q_d + \bar{q}_u \\
\tilde{\chi}^-_{1} \rightarrow \tilde{\chi}^0_{1} + \ell + \bar{\nu}
$$

where $q_d$ ($q_u$) denotes a charge $-1/3$ ($2/3$) quark. The two-body decays are forbidden if the chargino is lighter than $\sim 180$ GeV in the wino region, and in most of the parameter space in the higgsino region (see Fig. 1).

Now we concentrate on the three body leptonic decay of the chargino (1). In the lowest order of the electroweak couplings it proceeds via the exchange of $W$, charged Higgs, slepton, or sneutrino. The Feynman graphs are shown in Fig. 2. If the decay is dominated by the $W$ exchange, the branching ratios are determined by gauge universality

$$
\frac{B_\tau}{B_e} \equiv \frac{\text{B}(\tilde{\chi}^-_{1} \rightarrow \tilde{\chi}^0_{1} \tau \nu)}{\text{B}(\tilde{\chi}^-_{1} \rightarrow \tilde{\chi}^0_{1} e \nu)} = \frac{\Gamma(\tilde{\chi}^-_{1} \rightarrow \tilde{\chi}^0_{1} \tau \nu)}{\Gamma(\tilde{\chi}^-_{1} \rightarrow \tilde{\chi}^0_{1} e \nu)} = 1
$$

(1)

(the lepton masses are neglected). Even when the sfermion exchanges contribute, the ratio of the branching ratios remains unity if the sfermions of different generations have a common mass. Deviation from this prediction thus signals the splitting of the third generation sleptons from the first/second generations. The $H^-$ exchange is negligible for the decay to electron or muon, but not necessarily so for the tau decay, especially when $\tan \beta$ is large. This gives additional flavor-dependent effect, but it turns out to be not so important.

If the lepton mass and Yukawa coupling are neglected, only the wino component of $\tilde{\chi}^-_{1}$ interacts and the right-hand component of the charged lepton and the right-handed sfermion totally decouple. The charged Higgs also does not contribute. The decay rate in this case depends on one additional parameter other than those of the chargino-neutralino sector, which is the
mass of the left-handed sleptons ($\tilde{\nu}$ and $\tilde{\ell}_L$ are split by the $D$ term effect proportional to $m_2^2 \cos 2\beta$). This applies to the selectron and smuon decays.

For tauonic decay we have to retain the Yukawa coupling (though we neglect the kinematic tau mass), through which the right-handed tau/stau components and charged Higgs affect the amplitude. We find that the dependence of the rate on these masses is weak, unless these particles are much lighter than the left-handed sleptons.

We now show the results of the calculation of the $\tau/e$ ratio. We fix the chargino mass $m(\tilde{\chi}^-_1) = 150$ GeV, which is under the real $W$ threshold for any $M_2/\mu$. The results are not sensitive to the chargino mass as long as we stay below the threshold. The decay rates are calculated for several values of $M_2/\mu$ and $\tan \beta$, varying the slepton masses $m(\tilde{e}_L)$ and $m(\tilde{\tau}_L)$.

The right-handed sleptons are assumed to be degenerate with the left-handed sleptons of the same flavor. The results change very slightly if the right-handed sleptons are half as heavy. The left-right mixing is also neglected. Although the mixing may be substantial for staus, the decay rate is essentially determined by the left-left element of the sfermion mass matrix in most cases.

In Fig. 3, we show the $\tau/e$ ratio for $\tan \beta = 50$ for $M_2/\mu = 0.1, 0.4$ and 1. The ratio drastically deviates from unity in the gaugino region, even when the slepton mass is much larger than the chargino mass. The ratio can be as large as ten in some parameter region, although the sfermions are much heavier than the $W$ boson. The reason of this behavior is that the bino, which comprise the largest part of the lightest neutralino has no gauge coupling. The decay via virtual $W$ occurs either via the small wino component of $\tilde{\chi}_1^0$ or the higgsino component of both $\tilde{\chi}_1^-$ and $\tilde{\chi}_1^0$.

The behavior of the curves in Fig. 3(a) may be understood in the following way. If the $W$ exchange is negligible, the branching ratio is controlled by the mass of the exchanged sleptons and we find

$$B_{\tau}/B_e \approx m_{\tilde{e}/2}/m_{\tilde{\nu}}. $$

This dependence is approximately realized in the lower left region of Fig. 3(a), in which both the sleptons are relatively light. In the lower-right region, the selectron exchange becomes smaller than the $W$ exchange, so the above behavior switches to

$$B_{\tau}/B_e \approx m_{W}/m_{\tilde{\nu}}. $$

On the diagonal line $m_{\tilde{e}} = m_{\tilde{\nu}}$, we expect $B_{\tau}/B_e = 1$. Slight deviation of
the equal branching curve from the diagonal line in Fig. 3(a) is due to the charged Higgs exchange (We have taken $m_H = 250$ GeV).

The importance of the Higgs exchange can be seen from Fig. 4, in which we plot the equal-BR lines $B_\tau/B_e = 1$ for different Higgs masses. We can see that the charged Higgs has little effect if its mass is larger than, say, twice as the slepton mass.

In the mixed region $M_2/\mu \sim 1$, the sfermion mass dependence is rather weak since the $W$ exchange gives dominant contribution (the couplings are similar and there is no mass suppression). In the higgsino region (not shown) the sfermion couplings are essentially the Yukawa couplings and the branching ratios are insensitive to the sfermion mass.

In Fig. 5, the ratio $B_\tau/B_e$ is plotted for tan $\beta = 4$ and $-50$. The deviation is larger for negative tan $\beta$ (equivalently negative $\mu$). This comes from the fact that the higgsino component in $\tilde{\chi}^-_1$ is smaller for negative tan $\beta$. The deviation is somewhat milder for smaller tan $\beta$.

To summarize, we have demonstrated that the measurement of the branching ratios of the three-body chargino decays can give information on the mass of the exchanged sfermions. The flavor nonuniversality of the leptonic branching ratios implies the flavor nondegeneracy of sleptons unless the charged Higgs is light. The effect is especially prominent when the chargino is wino-like and stronger for larger tan $\beta$. The flavor dependence of slepton masses, which may cast a light to the mechanism of supersymmetry breaking, may be thus probed even when the sleptons cannot be directly produced.

The measurement of the branching ratios does not fix both $m(\tilde{e})$ and $m(\tilde{\tau})$. If selectron (therefore electron sneutrino) is not too heavy, the mass $m(\tilde{\nu}_e)$ may be extracted from the differential chargino pair production cross section [14]. If this is the case, determination of both slepton masses is possible.

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Fig. 1. Mass difference between $\tilde{\chi}_1^-$ and $\tilde{\chi}_1^0$. The two decay $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-$ is allowed only in the shaded region.

Fig. 2. Feynman diagrams for $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell^- \bar{\nu}$.

Fig. 3. The ratio $B_\tau / B_e$ for $m(\tilde{\chi}_1^-) = 150$ GeV, $\tan \beta = 50$, $m(H^-) = 250$ GeV, with (a) $M_2/\mu = 0.1$; (b) 0.4; (c) 1.

Fig. 4. The equal-BR lines $B_\tau / B_e = 1.0$ for $m(\tilde{\chi}_1^-) = 150$ GeV, $M_2/\mu = 0.1$, $\tan \beta = 50$, with $m(H^-) = 200, 250, 300, 400, 500, 1000$ GeV.

Fig. 5. The ratio $B_\tau / B_e$ for $m(\tilde{\chi}_1^-) = 150$ GeV, $M_2/\mu = 0.1$, $m(H^-) = 250$ GeV, with (a) $\tan \beta = -50$, (b) 4.
Figure 1
Figure 2
Figure 3(a)
Figure 3(b)
Figure 3(c)
Figure 4
Figure 5(a)
Figure 5(b)