Can Stop be Light Enough ?

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Abstract

We examine a possibility for existence of a light supersymmetric partner of the top quark (stop) with mass \(15 \sim 20\) GeV in the framework of the minimal supergravity GUT model. Such light stop could explain the slight excess of the high \(p_T\) cross section of the \(D^{\pm}\)-meson production in two-photon process at TRISTAN. We point out that the existence of such stop could change the dominant decay mode of some particles and could weaken substantially present experimental bounds on the supersymmetric parameter space. It seems that there is a finite parameter region allowing existence of the light stop even if we consider the present experimental data. Inversely, if the light stop was discovered at TRISTAN, masses and mixing parameters of the other SUSY partners as well as masses of the Higgs and the top will be severely constrained, for example, \(m_f \approx 75\) GeV, \(m_{\tilde{W}} \approx 55\) GeV, \(90\) GeV \(\leq m_{\tilde{L}} \leq 130\) GeV, \(100\) GeV \(\leq m_{\tilde{q}} \leq 150\) GeV, \(m_h \approx 60\) GeV and \(115\) GeV \(\leq m_t \leq 135\) GeV. Some phenomenological implications on the present and future experiments are also discussed.

1 Introduction

Recently, Enomoto et al. in TOPAZ group at TRISTAN have reported the slight excess of the high \(p_T\) cross section of the \(D^{\pm}\)-meson production in two-photon process [1]. While the disagreement between the measured value and the standard model prediction is 1.5\(\sigma\) level, there is a exciting way to interpret this enhancement. It is the pair production of the supersymmetric (SUSY) partner of the top quark (stop) at \(e^+e^-\) collision, \(e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1^*\) [2, 3, 4]. Since the stop will decay into the charm-quark plus the lightest neutralino [3], which can be regarded as the lightest SUSY particle (LSP), the signature of events will be the charm-quark pair plus large missing momentum. This signature would be resemble to

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the charmed-hadron production at the two-photon process at $e^+e^-$ colliders. Enomoto et al. have pointed out that the stop with mass about 15GeV and the neutralino with mass about 13GeV could well explain the experimental data.

It is natural to ask, "Have not already been such light stop and neutralino excluded by LEP or Tevatron experiments?" and "Could such light stop be favored theoretically?" In this paper we examine the possibility for existence of the light stop and the neutralino in the minimal supergravity GUT (MSGUT) scenario taking into account of the present experimental bounds on the SUSY parameter space. Here we consider only the bounds from collider data and do not concern rather model dependent bounds from the proton decay experiments and the dark matter searches.

2 Light stop: its theoretical bases

In the framework of the MSSM, the stop mass matrix in the $(\tilde{t}_L, \tilde{t}_R)$ basis is expressed by

$$M^2_{\tilde{t}} = \begin{pmatrix} m^2_{\tilde{t}_L} & a_t m_t \\ a_t m_t & m^2_{\tilde{t}_R} \end{pmatrix},$$

(1)

where $m_t$ reads the top mass. The SUSY mass parameters $m^2_{\tilde{t}_{L,R}}$ and $a_t$ are parametrized in the following way:

$$m^2_{\tilde{t}_L} = \tilde{m}^2_{Q_3} + m^2_Z \cos 2\beta \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) + m^2_t,$$

(2)

$$m^2_{\tilde{t}_R} = \tilde{m}^2_{U_3} + \frac{2}{3} m^2_Z \cos 2\beta \sin^2 \theta_W + m^2_t,$$

(3)

$$a_t = A_t + \mu \cot \beta,$$

(4)

where $\tan \beta$, $\mu$ and $A_t$ denote the ratio of two Higgs vacuum expectation values ($= v_2/v_1$), the SUSY Higgs mass parameter and the trilinear coupling constant, respectively. The soft breaking masses of third generation doublet $\tilde{m}_{Q_3}$ and the up-type singlet $\tilde{m}_{U_3}$ squarks are related to those of first (and second) generation squarks as

$$\tilde{m}^2_{Q_3} = \tilde{m}^2_{Q_1} - I,$$

(5)

$$\tilde{m}^2_{U_3} = \tilde{m}^2_{U_1} - 2I,$$

(6)

where $I$ is a function proportional to the top quark Yukawa coupling $\alpha_t$ and is determined by the renormalization group equations in the MSGUT. Throughout of this paper we adopt the notation in Ref.[9].

There are two origins for lightness of the stop compared to the other squarks and sleptons, i) smallness of the diagonal soft masses $m^2_{\tilde{t}_L}$ and $m^2_{\tilde{t}_R}$ and ii) the left-right stop mixing. Both effects are originated from the large Yukawa interaction of the top. The origin i) can be easily seen from Eqs.(2)~(6). The diagonal mass parameters $m^2_{\tilde{t}_L}$ and $m^2_{\tilde{t}_R}$ in Eq.(1) have possibly small values owing to the negative large contributions of $I$ proportional to $\alpha_t$ in Eqs.(3) and (4). It should be noted that this contribution is also

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important in the radiative SU(2)×U(1) breaking in the MSGUT. The Higgs mass squared
has similar expression to Eqs.(5) and (6) ;

$$\tilde{m}_{H_2}^2 = \tilde{m}_{L_1}^2 - 3I,$$

(7)

where $\tilde{m}_{L_1}^2$ denotes the soft breaking mass of first generation doublet slepton. The large
contribution of $I$ enables $\tilde{m}_{H_2}^2$ to become negative at appropriate weak energy scale. In
order to see another origin ii) we should diagonalize the mass matrix Eq.(1). The mass
eigenvalues are obtained by

$$m_{t_1}^2 = \frac{1}{2} \left[ m_{t_L}^2 + m_{t_R}^2 \pm \left( (m_{t_L}^2 - m_{t_R}^2)^2 + (2a_t m_t)^2 \right)^{1/2} \right].$$

(8)

and the corresponding mass eigenstates are expressed by

$$\left( \tilde{t}_1 \right) = \left( \tilde{t}_L \cos \theta_t - \tilde{t}_R \sin \theta_t \right) \left( \tilde{t}_L \sin \theta_t + \tilde{t}_R \cos \theta_t \right)^*,$$

(9)

where $\theta_t$ denotes the mixing angle of stops :

$$\sin 2\theta_t = \frac{2a_t m_t}{\sqrt{(m_{t_L}^2 - m_{t_R}^2)^2 + 4a_t^2 m_t^2}}.$$ (10)

$$\cos 2\theta_t = \frac{m_{t_L}^2 - m_{t_R}^2}{\sqrt{(m_{t_L}^2 - m_{t_R}^2)^2 + 4a_t^2 m_t^2}}.$$ (11)

We see that if SUSY mass parameters and the top mass are the same order of magnitude, small $m_{t_1}$ is possible owing to the cancellation in the expression Eq. 8.

After the mass diagonalization we can obtain the interaction Lagrangian in terms of
the mass eigenstate $\tilde{t}_1$. We note, in particular, that the stop coupling to the Z-boson
($\tilde{t}_1^{\dagger} \tilde{t}_1 Z$) depends sensitively on the mixing angle $\theta_t$. More specifically, it is proportional to

$$C_{\tilde{t}_1} \equiv \frac{2}{3} \sin^2 \theta_W - \frac{1}{2} \cos^2 \theta_t.$$ (12)

Note that for a special value of $\theta_t \sim 0.98$, the Z-boson coupling completely vanishes 3.

### 3 Present bounds on stop mass

Before discussion of experimental bounds on the stop mass $m_{t_1}$, we examine the decay
modes of the stop. In the MSSM, the stop lighter than the other squarks and gluino
can decay into the various final states : $\tilde{t}_1 \rightarrow t \tilde{Z}_1 (a), b\tilde{W}_1 (b), b\tilde{b} (c), b\nu \bar{\nu} (d), bWZ (e), bff' \tilde{Z}_1 (f), c\tilde{Z}_1 (g)$, where $\tilde{Z}_1, \tilde{W}_1, \nu$ and $\ell$, respectively, denote the lightest neutralino, the lighter chargino, the sneutrino and the charged slepton. If we consider the light stop with mass lighter than 20GeV, the first five decay modes (a) to (e) are kinematically forbidden due to the model independent lower mass bounds for respective particles ; $m_t \gtrsim 90$GeV, $m_{W_1} \gtrsim 45$GeV, $m_{t_\ell} \gtrsim 45$GeV and $m_{\nu} \gtrsim 40$GeV. So there left (f) and (g). Hikasa
and Kobayashi 2 have shown that the one-loop mode $\tilde{t}_1 \rightarrow c\tilde{Z}_1 (g)$ dominates over the
four-body mode $\tilde{t}_1 \to b ff' Z_1$ (f). It is absolutely true in the case considered here, because the mode (f) is negligible by the kinematical suppression, $m_\tilde{t}_1 \sim m_{Z_1} + m_b$. So we can conclude that such light stop will decay into the charm quark jet plus the missing momentum taken away by the neutralino with almost 100% branching ratio. Note that the width of stop in this case is very small, i.e., the order of magnitude of eV.

Naively, it will be expected that Tevatron and/or LEP can set severe bounds on the stop mass through the processes $gg \to \tilde{t}_1 \tilde{t}_1^* \to c\bar{c}Z_1\bar{Z}_1$ (Tevatron) and/or $Z \to \tilde{t}_1 \tilde{t}_1^*$ (LEP). However, the situation is not so obvious. Baer et al. [11] have performed the analyses of the experimental data of 4pb$^{-1}$ integrated luminosity Tevatron running, and have obtained the results that the stop could easily be escaped the detection if $m_{Z_1} \gtrsim 10$GeV. Such large neutralino mass could make the charm quark jets softer. Consequently the stop production cross section plotted against the missing transverse energy becomes smaller.

Moreover, we should point out that LEP cannot exclude the light stop for appropriate mixing angle $\theta_t$. In Fig.1, we show the excluded region in $(\theta_t, m_{\tilde{t}_1})$ plane by LEP in terms of $\Delta \Gamma_Z < 35.1$MeV (95% C.L.) [12], where we included the QCD correction in the calculation [3]. We find that there is no bound on the stop mass if the mixing angle $\theta_t$ is larger than about 0.6. The origin of such sensitivity of $\Gamma(Z \to \tilde{t}_1 \tilde{t}_1^*)$ is in the fact that the $\tilde{t}_1 \tilde{t}_1^* Z$ coupling is proportional to $C_{\tilde{t}_1}$ [12]. TRISTAN have ever settled the lower mass bounds on squarks $m_\tilde{q} \gtrsim 5$GeV assuming massless photino in terms of the direct search $e^+e^- \to q\bar{q}'$ [13]. Those bounds, however, are invalidated if $m_{\tilde{q}} - m_{Z_1} < 8$GeV. Although we know a bound from direct $\tilde{t}_1$ search at DELPHI reported by Fisher [14], we do not concern it here because the adopted value of mass difference $m_{\tilde{t}_1} - m_{Z_1}$ in their analyses is unknown for us. Recently Okada [15] has investigated possible bounds on masses of the stop and the neutralino from the experimental data of the $b \to s\gamma$ decay. He has shown that the light stop with mass $m_{\tilde{t}_1} \lesssim 20$GeV has not been excluded by the data. After all, we can conclude that there is no bound on the stop mass for $m_{Z_1} \lesssim 10$GeV and $\theta_t \lesssim 0.6$ if $m_{\tilde{t}_1} - m_{Z_1} < 8$GeV.

4 Present bounds on gaugino parameters

In the MSSM, masses and mixing parameters of the gaugino-higgsino sector are determined by three parameters $\mu$, $\tan \beta$ and $M_2$, where $M_2$ denotes the soft breaking SU(2) gaugino mass. Some regions in $(\mu, \tan \beta, M_2)$ parameter space have already excluded by the negative searches for the SUSY particles at some collider experiments. First, we concern the experimental data at LEP ; i) lower bound on the mass of lighter chargino, $m_{W_L} \gtrsim 45$GeV, ii) upper bound on the branching ratio of the visible neutralino modes of the $Z$, $\text{BR}(Z \to \text{vis.}) \equiv \sum_{i,j} \Gamma(Z \to \bar{Z}_i Z_j)/\Gamma_Z^{\text{tot}} < 5 \times 10^{-5}$ [17], and iii) upper bound on the invisible width of the $Z$, $\Gamma(Z \to \bar{Z}_1 \bar{Z}_1) < 16.2$MeV [12]. In Fig.2 we show the region excluded by the experimental data i) $\sim$ iii) in $(\mu, M_2)$ plane for $\tan \beta = 2$. We also plot a contour of $m_{Z_1} = 13$GeV which can explain the TRISTAN data as mentioned above. First we realize that the neutralino with mass 13GeV can be allowed in the range $-160$GeV $\lesssim \mu \lesssim -110$GeV for $\tan \beta = 2$. Note that the contour of $m_{Z_1} = 13$GeV lies in the excluded region for $\mu > 0$. If we take larger (smaller) values of $\tan \beta$, the allowed
region become narrower (wider). We find that the allowed region disappears for \( \tan \beta > 2.3 \). Second we see that \( m_{\tilde{Z}_1} = 13 \text{GeV} \) corresponds to \( M_2 \approx 22 \text{GeV} \) in the allowed region and we can find that this correspondence is independent on the values of \( \tan \beta \). Consequently, we can take \( M_2 = 22 \text{GeV} \) as an input value in the following calculation. Allowed region in \((\mu, \tan \beta)\) plane fixed by \( M_2 = 22 \text{GeV} \) is shown in Fig.3. Additional bounds on the \((\mu, \tan \beta)\) parameter space from the negative search for the neutral Higgs boson at LEP will be discussed bellow. It is worth mentioning that the lightest neutralino \( \tilde{Z}_1 \) is almost photino \( \tilde{\gamma} \) in the allowed parameter range in Fig.3. In fact, the photino component of the neutralino is larger than 99% in the range.

Next we should discuss bounds on the gaugino parameters from the hadron collider experiments. If we assume the GUT relation,

\[
m_{\tilde{g}} = M_3 = \frac{\alpha_s}{\alpha} \sin^2 \theta_W M_2
\]

(13)
in the MSGUT, the gluino mass \( m_{\tilde{g}} \) bounds from the hadron colliders could be converted into the bounds on \( M_2 \) [16]. The gluino mass bound at CDF taken into account of the cascade decays \( \tilde{g} \to q\tilde{q}Z_{2,3,4} \) and \( \tilde{g} \to ud\tilde{W}_{1,2} \) [18] as well as the direct decay \( \tilde{g} \to q\tilde{q}Z_1 \) has reported as [19]

\[
m_{\tilde{g}} \gtrsim 95 \text{GeV} \quad \text{(90\% C.L.)}
\]

(14)
for \( \mu = -250 \text{GeV} \) and \( \tan \beta = 2 \). This bound can be easily converted into the bound on \( M_2 \) by Eq.(13) as \( M_2 \gtrsim 28 \text{GeV} \), which rejects the the above fixed value, \( M_2 = 22 \text{GeV} \). (Note that the GUT relation (13) depends sensitively on \( \sin^2 \theta_W \) and \( \alpha_s \). Here we take \( \sin^2 \theta_W = 0.232 \) and \( \alpha_s = 0.113 \). ) We must concern, however, a fact that the bound (14) is obtained based on the assumption that \( m_{\tilde{t}_1} > m_{\tilde{g}} \) and the gluino can not decay into the stop. It is not the case we consider here. In fact, the gluino can decay into the stop pair, \( \tilde{g} \to \tilde{t}_1\tilde{t}_1^* \tilde{Z}_1 \), which becomes another seed for the cascade decay. In Fig.4 we show the \( m_{\tilde{g}} \) dependence of the branching ratio of gluino, where we include the mode \( \tilde{g} \to \tilde{t}_1\tilde{t}_1^* \tilde{Z}_1 \) and sum up quark flavors \( q, q' = u, d, c, s \). We take \( \tan \beta = 2, \mu = -150 \text{GeV}, \) \( m_{\tilde{t}_1} = 15 \text{GeV}, \theta_t = 0.7, m_t = 135 \text{GeV} \) and \( M_2 = 22 \text{GeV} \), and take \( m_{\tilde{g}} \) as a free parameter. The squark masses are taken as \( m_{\tilde{q}} = 2m_{\tilde{g}} \) (a) and \( m_{\tilde{q}} = 3m_{\tilde{g}} \) (b), where \( m_{\tilde{q}} \equiv m_{\tilde{q}_{L,R}} \). \( m_{\tilde{\tilde{Z}}_{L,R}} = m_{\tilde{\tilde{Z}}_{L,R}} = m_{\tilde{\tilde{Z}}_{L,R}} \). An arrow in the figure denotes the \( m_{\tilde{g}} \) value determined by the GUT relation. The branching ratio of the direct decay mode \( \tilde{g} \to q\tilde{q}Z_1 \), which is important in the \( \tilde{g} \) search in terms of large \( \not{p}_T \) signature, is reduced substantially as \( \text{BR}(\tilde{g} \to q\tilde{q}Z_1) \gtrsim 50\% \) (15\%), even for the light gluino with mass \( m_{\tilde{g}} \gtrsim 60 \text{GeV} \) for \( m_{\tilde{q}} = 2m_{\tilde{g}} \) (\( m_{\tilde{q}} = 3m_{\tilde{g}} \)). Therefore, we should reconsider the UA2 bound \( m_{\tilde{g}} \gtrsim 79 \text{GeV} \) [20] obtained under the assumption \( \text{BR}(\tilde{g} \to q\tilde{q}Z_1) \sim 100\% \) as well as the CDF bound (14). For the value \( m_{\tilde{g}} = 74 \text{GeV} \) determined by the GUT relation, \( \text{BR}(\tilde{g} \to q\tilde{q}Z_1) \sim 20\% \) (4\%) for \( m_{\tilde{q}} = 2m_{\tilde{g}} \) (\( m_{\tilde{q}} = 3m_{\tilde{g}} \)), which should be compared with \( \text{BR}(\tilde{g} \to q\tilde{q}Z_1) \sim 70\% \) obtained when there is no stop mode. We can find that if we take larger values of \( m_{\tilde{q}} \), \( \text{BR}(\tilde{g} \to q\tilde{q}Z_1) \) is reduced rapidly. In this case the Tevatron bound (14) would be diminished significantly. This is because the width of stop mode \( \Gamma(\tilde{g} \to \tilde{t}_1\tilde{t}_1^* \tilde{Z}_1) \) does not depend on \( m_{\tilde{q}} \) but all the other widths become smaller for larger values of \( m_{\tilde{q}} \). While all squark masses are independent parameters in the MSSM, they are determined by small numbers of input parameters in the MSGUT. Hereafter we adopt the GUT relation and will reconsider the Tevatron bound after presenting the results of the MSGUT analyses. Note that if we
remove the GUT relation, the gluino can be heavy with no relation with \( M_2 \) and \( m_{\tilde{Z}_1} \) and \( \text{BR}(\tilde{g} \to q\bar{q}\tilde{Z}_1) \) can be small.

5  **MSGUT analysis**

Before presenting our results for the analysis, we will summarize briefly the calculational scheme in the MSGUT \(^3\). In this scheme the independent parameters, besides the gauge and Yukawa couplings, at GUT scale \( M_X \) are the SUSY Higgs mass parameter \( \mu(M_X) = \mu_\infty \) and three soft breaking mass parameters: the common scalar mass \( \tilde{m}^2_\tilde{H}(M_X) = \tilde{m}^2_\tilde{H}(M_X) = m_X^2 \), the common gaugino mass \( \tilde{M}_3(M_X) = \tilde{M}_3^2(M_X) = M_3^2(M_X) = M_\infty \) and the trilinear coupling \( A_t(M_X) = A_\mu(M_X) = A_t(M_X) = \ldots = A_\infty \). As usual, we take the Higgs mixing parameter \( B \) as \( B(M_X) = A_\infty - m_\infty \). All the physical parameters go from \( M_X \) down to low energies governed by the renormalization group equations (RGE) \(^3\). In the following we neglect all Yukawa couplings except for the top. This is not a bad approximation as long as \( \tan\beta \) is not too large \((\ll m_t/m_b)\), which is the case we consider here, \( \tan\beta \sim 2.3 \).

As for the evolution of the gauge couplings \( \alpha_i(t) \) and the gaugino masses \( M_i(t) \), we take the input values \( \alpha_3^{-1}(m_Z) = 128.8 \) and \( \sin^2\theta_W = 0.232 \). Assuming the SUSY scale is not too different for \( m_Z \), we may use the SUSY beta function at all scales above \( m_Z \) for simplification. Then one finds \( M_X = 2.1 \times 10^{16} \text{GeV}, \alpha_3^{-1}(M_X) = \alpha_2^{-1}(M_X) = \alpha_1^{-1}(M_X) = 24.6 \) and \( \alpha_3(m_Z) = 0.113 \). Moreover, the RGE for gaugino masses are easily solved as

\[
M_i(t) = \alpha_i(t) \frac{M_\infty}{\alpha_\infty}.
\]  

After solving the all other RGE for the physical parameters, all physics at weak scale \( m_Z \) are determined by the six parameters \((m_\infty, A_\infty, M_\infty, \mu, \tan\beta, m_t)\). There are, moreover, two conditions imposed on the parameters to have the correct scale of \( SU(2) \times U(1) \) breaking. So we can reduce the number of the independent parameters to four out of the six. Here we take the four independent input parameters as \((M_\infty, \mu, \tan\beta, m_t)\). As we have discussed earlier, furthermore, we can fix one of input value, \( M_2 = 22 \text{GeV} \), which corresponds to \( M_\infty = 26.7 \text{GeV} \) for \( \sin^2\theta_W = 0.232 \) (see Eq.(15)). After all, there remain the only three parameters \((\mu, \tan\beta, m_t)\).

We seek numerically solutions to give the light stop with mass \( m_{\tilde{Z}_1} = 13 \text{GeV} < m_{\tilde{t}_1} < 20 \text{GeV} \) varying the three parameters \((\mu, \tan\beta, m_t)\). The results are shown in Fig.5, which is the same parameter space in Fig.3. Each hatched area corresponds to the region allowing \( m_{\tilde{Z}_1} < m_{\tilde{t}_1} < 20 \text{GeV} \) for the fixed \( m_t \) value. The upper (lower) line of each area corresponds to \( m_{\tilde{t}_1} = m_{\tilde{Z}_1} = 13 \text{GeV} \) \((m_{\tilde{t}_1} = 20 \text{GeV})\). We also plot the mass \( m_h \) contours of the lighter CP-even neutral Higgs boson as well as the LEP bounds from the data discussed above. First we realize that there is rather narrow but finite range allowing existence of the light stop, if the top was slightly light too, \( m_t \sim 135 \text{GeV} \). Second we find that the light stop solutions give inevitably the light Higgs boson, \( m_h \sim 60 \text{GeV} \). While we have included the radiative correction in the calculation of the Higgs mass \(^{21}\), deviations \( \delta m_h \) from the tree level results are not so large, \(|\delta m_h| \lesssim 2 \text{GeV}\). The neutral Higgs is standard Higgs like, i.e., \( \sin(\beta - \alpha) \simeq 1 \), where \( \alpha \) denotes the Higgs mixing angle.
So we should take care the lower mass bound on $m_h$ by the MSSM Higgs search at
LEP,

$$m_h \gtrsim 50 \text{GeV} \quad (95\% \text{C.L.})$$

(16)

for $\sin(\beta - \alpha) \simeq 1$. Here we must consider the signature of Higgs production at
LEP. We can find that the neutral Higgs will have dominant decay mode $h \to \tilde{t}_1 \tilde{t}_1^*$ with
almost 100% branching ratio as we will discuss bellow. In this case energies of visible
jets from the Higgs would become softer and it can be smaller than the detection lower
cuts. It is plausible that the bound (16) would be weakened although we need a detailed
Monte Carlo study to obtain rigorous bounds from the LEP experiments. Here we assume
a conservative bound $m_h \gtrsim 45 \text{GeV}$. Adopting such bound, we can choose three typical
parameter sets (A), (B) and (C), denoted in Fig.5. The set (A) [(B)] has the largest
[sallest] scalar fermion masses and the smallest [largest] lighter chargino mass. The
set (C) corresponds to the almost center point in the allowed range. Input and output
values of the parameters of the sets (A), (B) and (C) are presented in Table 1. We find
that masses and mixing parameters are severely constrained, for example, $m_{\tilde{W}_1^-} \sim 55 \text{GeV},$
$90 \text{GeV} \lesssim m_{\tilde{\tau}} \lesssim 130 \text{GeV}, 100 \text{GeV} \lesssim m_{\tilde{\nu}} \lesssim 150 \text{GeV}$ and $0.65 \lesssim \theta_t \lesssim 0.75$. Note that only
the upper limits on $m_{\tilde{W}_1^-}$ and $\theta_t$ and the lower limits on $m_{\tilde{\tau}}$ and $m_{\tilde{\nu}}$ depend on the tentative
assumption $m_h \gtrsim 45 \text{GeV}$.

6 Phenomenological implications

Now we are in position to discuss some consequence of the light stop scenario in the
MSGUT and give strategies to confirm or reject such possibility in the present and future
experiments. Some numerical results are calculated with the typical parameter sets (A),
(B) and (C).

The existence of the light stop with mass $15 \sim 20 \text{GeV}$ will alter completely decay
patterns of some ordinary and SUSY particles (sparticles). First we discuss the top decay
[11, 23]. In our scenario, the top can decay into final states including the stop; $t \to \tilde{t}_1 \tilde{Z}_1,$
$\tilde{t}_1 \tilde{Z}_2$ and $\tilde{t}_1 \tilde{g}$. Branching ratios of the top for the typical parameter sets are presented in
Table 2. We find that the gluino mode $t \to \tilde{t}_1 \tilde{g}$ has 40~50% branching ratio and dominates
over the standard mode $t \to bW^+$ in almost whole allowed parameter region. Strategies
for the top search at Tevatron would be forced to change because the leptonic branching
ratios of the top would be reduced by the dominance of the stop-gluino mode.

Decay patterns of the Higgs particles will be changed too. The lighter CP-even neutral
Higgs decays dominantly into the stop pair, $h \to \tilde{t}_1 \tilde{t}_1^*$, owing to the large Yukawa coupling
of the top. In rough estimation, we obtain

$$\text{BR}(h \to \tilde{t}_1 \tilde{t}_1^*) \simeq \frac{1}{1 + \frac{3m_{\tilde{t}}^2 m_{\tilde{Z}}^2}{2m_t^2}} \simeq 1.$$  (17)

This fact would change the experimental methods of the Higgs searches at the present and
future collider experiments. More detail analyses of the charged [24] and neutral Higgs
bosons are presented separately.
Now we discuss briefly the light stop impact on the sparticle decays. The lightest charged sparticle except for the stop is the lighter chargino $\tilde{\chi}_1^\pm$. The two body stop mode $\tilde{W}_1 \rightarrow b\tilde{t}_1$ would dominate over the conventional three body mode $\tilde{W}_1 \rightarrow f\bar{f}Z_1$. As a consequence, it would be difficult to use the leptonic signature in the chargino search at $e^+e^-$ and hadron colliders. Since the chargino $\tilde{W}_1$, the neutral Higgs $h$ and the gluino $\tilde{g}$, whose dominant decay modes are respectively $\tilde{W}_1 \rightarrow b\tilde{t}_1$, $h \rightarrow \tilde{t}_1\tilde{t}_1^*$ and $\tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1^*Z_1$, are copiously produced in the other sparticle decay, many stops would be expected in the final states of the sparticle production. For example, $\tilde{\ell}_L \rightarrow \nu \tilde{W}_1 \rightarrow \nu (b\tilde{t}_1)$, $\tilde{q}_{L,R} \rightarrow q\tilde{g} \rightarrow q(\tilde{t}_1\tilde{t}_1^*Z_1)$, $\tilde{q}_{L} \rightarrow q'\tilde{W}_1 \rightarrow q'(b\tilde{t}_1)$ and $\tilde{Z}_{i(i\neq 1)} \rightarrow \tilde{Z}_1 h \rightarrow \tilde{Z}_1(\tilde{t}_1\tilde{t}_1^*)$. Note that the dominant decay modes of the right-handed sleptons would be unchanged, i.e., $\text{BR}(\tilde{\ell}_R \rightarrow \ell\tilde{Z}_1) \simeq 100%$.

Needless to say, all experimental groups, AMY, TOPAZ and VENUS, at TRISTAN should perform a detail data analyses to confirm or reject the exciting scenario. Furthermore, we can see that the stop and its relatively light accompaniments, the gluino $\tilde{g}$, light neutralinos $\tilde{Z}_{1,2}$, and neutral Higgs $h$, should be visible at LEP, SLC, HERA and Tevatron. Especially, LEP could search whole allowed region presented in Figs.1 and 5 in terms of the width of $Z$-boson. First we find from Table 1, the stop mixing angle $\theta_t$ is severely limited as $0.65 \lesssim \theta_t \lesssim 0.75$ in the allowed range in Fig.5. It should be noted that the upper bound depends on the tentative assumption $m_h \lesssim 45$GeV. The larger (smaller) lower limit on $m_h$ gives slightly narrower (wider) range of $\theta_t$. On the other hand, the lower bound on $\theta_t$ is determined by the established limit $m_{\tilde{W}_1} \lesssim 45$GeV. It is interesting that $\theta_t \simeq 0.7$ is not input but output of the MSGUT calculation. The allowed values of $\theta_t$ with $m_{\tilde{t}_1} \sim 15$-$20$GeV are very close to present experimental limit from $\Delta\Gamma_Z$ measurement as depicted in Fig.1. We find that the stop contribution $\Gamma(Z \rightarrow \tilde{t}_1\tilde{t}_1^*)$ to $\Delta\Gamma_Z$ is larger than about $15$MeV for $\theta_t \sim 0.75$ and $m_{\tilde{t}_1} \lesssim 20$GeV. Second, the whole allowed region in Fig.5 can be explored by the precise measurement of BR($Z \rightarrow \text{vis.}$). In fact, the smallest value of the neutralino contribution $\sum_{i,j \neq 1} \Gamma(Z \rightarrow \tilde{Z}_i\tilde{Z}_j)/\Gamma_Z$ to BR($Z \rightarrow \text{vis.}$) is $1.1 \times 10^{-5}$ ($1.8 \times 10^{-5}$) for $m_h > 45$GeV ($m_h > 50$GeV). Of course, the Higgs $h$ search at LEP with the stop signature $h \rightarrow \tilde{t}_1\tilde{t}_1^*$ is very important to set further constraint on the allowed region. Clearly, the lighter chargino, $m_{\tilde{\chi}_1^+} \lesssim 55$GeV, would be visible at LEP II. Furthermore, there is a possibility that some sleptons will be discovered at $\sqrt{s} \simeq 200$GeV.

As mentioned before, Tevatron will play a crucial role in confirming or rejecting the light stop scenario in the MSGUT with the GUT relation. In this case the existence of relatively light gluino, $m_{\tilde{g}} \simeq 75$GeV, with substantially large decay fraction $\tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1^*Z_1$ is one of definite prediction. Values of branching ratios of the gluino for the typical parameter sets (A), (B) and (C) are tabulated in Table 3. The branching ratio of direct decay mode $\text{BR}(\tilde{g} \rightarrow q\tilde{q}\tilde{Z}_1) = 25 \sim 50\%$ is expected in the allowed range. These values are rather large compared to those in Fig.4(b). This is originated from the fact that allowed mass values of squarks except for the heavier stop $\tilde{t}_2$ are relatively small $m_{\tilde{q}} \lesssim 150$GeV. Those squarks could be within reach of Tevatron. Signatures of those squarks, however, would be unusual because of their cascade decays such as $\tilde{q}_{L,R} \rightarrow q\tilde{g} \rightarrow q(\tilde{t}_1\tilde{t}_1^*Z_1)$ and $\tilde{q}_{L} \rightarrow q'\tilde{W}_1 \rightarrow q'(b\tilde{t}_1)$. Anyway, there is a large possibility that some regions could have been excluded by Tevatron data. Detail Monte Carlo studies including the stop mode $\tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1^*Z_1$ are required at any cost. At least we expect that the region near the point corresponds to the set (B) could have been excluded because BR($\tilde{g} \rightarrow q\tilde{q}\tilde{Z}_1$) would be large enough to
make the $E_T$ signal events larger than its experimental upper limits. Note again that the light stop and neutralino can survive even after the negative search for the gluino and squarks at Tevatron if we remove the GUT relation Eq.(13). Removal of the GUT relation corresponds to the change of boundary conditions on the soft gaugino masses at the unification scale $M_X$. Owing to this change the RGE solution for the stop mass is modified and in turn we will get different allowed parameter region to Fig.5. The analyses based on such models will be presented elsewhere.

The $ep$ collider HERA could search the light stop through its pair production process $ep \to e \tilde{t}_1 \tilde{t}_1^* X$ via boson-gluon fusion \[23\]. The total cross section of the process is larger than about 10pb for $m_{\tilde{t}_1} \sim 20$GeV, which is independent on the mixing angle $\theta_t$. That is, $\sigma \sim 10$pb is expected for all parameters with $m_{\tilde{t}_1} \sim 20$GeV in the allowed range in Figs.1 and 5. Detail analyses with Monte Carlo studies including possible dominant background process $ep \to e\alpha\pi X$ can be found in Ref.\[24\]. The process $ep \to e \tilde{t}_1 \tilde{t}_1^* X$ is useful to confirm or reject the very light stop, but not to effective in determining model parameters in the MSSM such as the other sparticle masses as well as $\theta_t$. We have calculated another process

$$ep \to b\tilde{t}_1^* \nu X,$$

(18)

which is expected to be useful in the latter purpose because the cross section depends on $m_{\tilde{W}_1}, m_{\tilde{\nu}}, \theta_t$ and the mixing angles of $\tilde{W}_1$. The total cross section is obtained as $1.4 \times 10^{-3}$pb for the set (A) and $2.0 \times 10^{-2}$pb for the set (B). Although these values are rather small and the high luminosity would be needed to see, sensitivity on the SUSY parameters is rather high.

Here a comment on the $R$-parity breaking couplings of the stop may be in order. We have calculated not only the $R$-conserving process $ep \to e \tilde{t}_1 \tilde{t}_1^* X$ but also the $R$-breaking process $ep \to (\tilde{t}_1) \to eqX$ in Refs.\[20, 27\]. Latter process could have a distinctive signature, i.e., a sharp peak in the Bjorken parameter $x$ distribution. In our scenario of a very light stop, however, the strength of the $R$-parity (and lepton number) breaking coupling of the stop defined in the superpotential \[28\] :

$$W = \lambda'_{131} L_1 Q_3 D_1$$

(19)

can not be large enough for possible detection at HERA. This is because the coupling Eq.(13) with $\lambda'_{131} > 10^{-4}$ make the $R$-breaking stop decay mode $\tilde{t}_1 \to ed$ dominant and this fact contradicts $BR(\tilde{t}_1 \to c\tilde{Z}_1) \approx 100\%$ expected at TRISTAN.

Polarized initial electron beams at SLC and at any linear $e^+e^-$ colliders will be efficient to reveal the nature of left-right mixing in the stop sector, in other words, to measure the mixing angle of stop $\theta_t$. In Fig.6 we show the $\sqrt{s}$ dependence of the left-right asymmetry :

$$A_{LR} \equiv \frac{\sigma(e_L) - \sigma(e_R)}{\sigma(e_L) + \sigma(e_R)},$$

(20)

where $\sigma(e_{L,R}) \equiv \sigma(e^+ e^-_{L,R} \to \tilde{t}_1 \tilde{t}_1^*)$, which are obtained by

$$\sigma(e^+ e^-_{L,R} \to \tilde{t}_1 \tilde{t}_1^*)$$

(21)

$$= \frac{\pi \alpha^2}{s} \beta^3_{\tilde{t}_1} \left[ \frac{4}{3} C_{\tilde{t}_1} (v_e \pm a_e) \text{Re} \left( \frac{s}{D_Z} \right) + \frac{1}{4} C^2_{\tilde{t}_1} (v_e \pm a_e)^2 \frac{s}{D_Z} \right] (1 + \delta_{QCD}).$$

(22)
where \( \beta_{\tilde{t}_1} \equiv \sqrt{1 - 4m_{\tilde{t}_1}^2/s} \), \( D_Z \equiv s - m_Z^2 + im_Z \Gamma_Z \), \( v_e \equiv (-\frac{1}{2} + 2\sin^2 \theta_W) / (\sin^2 \theta_W \cos^2 \theta_W) \) and \( a_e \equiv -1/(2\sin^2 \theta_W \cos^2 \theta_W) \). In the asymmetric combination in Eq.(20) the photon contribution is cancelled out and \( A_{LR} \) is proportional to \( C_{\tilde{t}_1} \) Eq.(12). This is the reason for sensitive dependence on \( \theta_t \) of \( A_{LR} \) in Fig.6. Another important property is that \( A_{LR} \) is independent on the mass of stop \( m_{\tilde{t}_1} \) as well as on the QCD correction \( \delta_{QCD} \) since \( \beta_{\tilde{t}_1}^3 \) and \( 1 + \delta_{QCD} \) disappeared in the fractional combination of \( \sigma \) in \( A_{LR} \). Therefore, this method for measuring \( \theta_t \) will be applicable for the stop with any mass satisfying \( m_{\tilde{t}_1} < \sqrt{s}/2 \).

7 Conclusion

We have investigated the possibility for existence of the light stop \( m_{\tilde{t}_1} = 15 \sim 20 \text{GeV} \) and the neutralino \( m_{\tilde{Z}_1} \simeq 13 \text{GeV} \) in the MSGUT scenario taking into account of the present experimental bounds on the SUSY parameter space. We have pointed out that the existence of such stop could change the dominant decay mode of some particles. For example, the stop modes \( g \rightarrow \tilde{t}_1 \tilde{\nu}_1 \tilde{Z}_1 \) and \( h \rightarrow \tilde{t}_1 \tilde{\nu}_1 \) could dominate over respectively the conventional modes \( g \rightarrow \ell \bar{\nu} \tilde{Z}_1 \) and \( h \rightarrow b \bar{b} \) even for relatively light gluino and Higgs. As a consequence, present experimental bounds on the SUSY parameter space could be weakened considerably. It seems that there is a finite parameter region allowing existence of such light stop even if we consider the present experimental data. Inversely, it has been found that, if such light stop was discovered at TRISTAN, masses and mixing parameters of the other SUSY partners as well as masses of the Higgs and the top will be severely constrained, for example, \( m_{\tilde{g}} \simeq 75 \text{GeV} \), \( m_{\tilde{\nu}_1} \simeq 55 \text{GeV} \), \( 90 \text{GeV} \simeq m_{\tilde{\tau}_1} \simeq 130 \text{GeV} \), \( 100 \text{GeV} \simeq m_{\tilde{\chi}_1^0} \simeq 150 \text{GeV} \), \( 0.65 \simeq \theta_t \simeq 0.75 \), \( m_h \simeq 60 \text{GeV} \) and \( 115 \text{GeV} \simeq m_{\tilde{t}_1} \simeq 135 \text{GeV} \). Actually, the light stop and its relatively light accompaniments, the gluino \( \tilde{g} \), the light neutralinos \( \tilde{Z}_{1,2} \), and the neutral Higgs \( h \), should be visible near future at LEP, HERA and Tevatron. In fact, LEP and HERA could explore the whole allowed parameter region in terms of the precise measurement of the width of \( Z \) and by means of searching for the process \( ep \rightarrow e \tilde{t}_1 \tilde{\nu}_1 X \), respectively. There exists, moreover, special interest on Tevatron experiment, i.e., Tevatron could either discover or exclude the light gluino \( m_{\tilde{g}} \simeq 75 \text{GeV} \). If we could not discover such gluino, this fact would indicate invalidity of the GUT relation, in other words, the assumption of the common gaugino mass at \( M_X \). Experimental sign for violation of the GUT relation may be important to select a specific model out of a great number of string model candidates.

Recently, Altarelli et al. [29] have shown that the light stop \( m_{\tilde{t}_1} \simeq 50 \text{GeV} \) and light chargino \( m_{\tilde{W}_1} \simeq 60 \text{GeV} \) could well explain the precision data at LEP. Their result seems to support our light stop scenario. In this paper we have exemplified that if we discover the light stop we will be able to constrain severely all the SUSY parameters at the unification scale. We can conclude that, therefore, the discovery of the stop will bring us a great physical impact. Not only it will be the first signature of the top flavor and the supersymmetry but also it could shed a light on the physics at the unification scale.

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Figure Captions

Figure 1: Excluded region in $(\theta_t, m_{\tilde{t}_1})$ plane by LEP with $\Delta \Gamma_Z < 35.1\text{MeV}$.

Figure 2: Contour of $m_{\tilde{Z}_1} = 13\text{GeV}$ in $(\mu, M_2)$ plane for $\tan \beta = 2$. Excluded region by LEP is also depicted.

Figure 3: Allowed region in $(\mu, \tan \beta)$ plane for $M_2 = 22\text{GeV}$. Dashed line and dotted line respectively correspond to contour of $\text{BR}(Z \rightarrow vis) = 5 \times 10^{-5}$ and that of $m_{\tilde{W}_1} = 45\text{GeV}$, respectively.

Figure 4: $m_\tilde{g}$ dependence of branching ratios of gluino. Sum over quark flavors $q, q' = u, d, c, s$ are taken. Input parameters are $\tan \beta = 2, \mu = -150\text{GeV}, m_{\tilde{t}_1} = 15\text{GeV}, \theta_t = 0.7, m_t = 135\text{GeV}, M_2 = 22\text{GeV}$ and $m_\tilde{q} = 2m_\tilde{g}$ (a) and $m_\tilde{q} = 3m_\tilde{g}$ (b). An arrow in the figure denotes the $m_\tilde{g}$ value determined by the GUT relation.

Figure 5: Stop mass contours in $(\mu, \tan \beta)$ plane for fixed $m_t$. Each hatched area corresponds to the region $m_{\tilde{Z}_1} < m_{\tilde{t}_1} < 20\text{GeV}$. The upper (lower) line of each area corresponds to $m_{\tilde{t}_1} = m_{\tilde{Z}_1}$ ($m_{\tilde{t}_1} = 20\text{GeV}$). We also plot the mass $m_h$ contours as well as the LEP bounds. Points denoted by A, B and C are correspond to typical parameter sets in the text.

Figure 6: Total energy $\sqrt{s}$ dependence of left-right asymmetry for the stop production at $e^+e^-$ colliders. For comparison we also plot $A_{LR}$ for the up-type quark production.
Table 1: Typical parameter sets

| masses in GeV | A  | B  | C  |
|--------------|----|----|----|
| $M_2$        | 22 | 22 | 22 |
| $\tan \beta$ | 2.09 | 1.83 | 2.0 |
| $\mu$        | $-151$ | $-94.5$ | $-135$ |
| $m_t$        | 135 | 117 | 130 |
| $M_\infty$   | 26.7 | 26.7 | 26.7 |
| $m_\infty$   | 125.1 | 83.6 | 111.6 |
| $A_\infty$   | 332.2 | 206.8 | 293.3 |
| $\mu_\infty$ | $-132.8$ | $-78.4$ | $-116.7$ |
| $m_{\tilde{t}_1}$ | 14.6 | 15.4 | 15.5 |
| $m_{\tilde{t}_2}$ | 201.9 | 183.0 | 196.4 |
| $\theta_t$   | 0.66 | 0.72 | 0.68 |
| $m_{\tilde{b}_1}$ | 107.0 | 93.0 | 102.0 |
| $m_{\tilde{b}_2}$ | 142.9 | 108.5 | 131.2 |
| $m_{\tilde{u}_L}$ | 136.0 | 100.4 | 124.0 |
| $m_{\tilde{u}_R}$ | 138.5 | 103.1 | 126.6 |
| $m_{\tilde{d}_L}$ | 150.0 | 116.3 | 138.6 |
| $m_{\tilde{d}_R}$ | 142.7 | 107.9 | 131.0 |
| $m_{\tilde{\ell}_L}$ | 132.0 | 92.5 | 119.0 |
| $m_{\tilde{\ell}_R}$ | 130.3 | 90.2 | 117.2 |
| $m_{\tilde{\nu}}$ | 115.8 | 71.5 | 101.7 |
| $m_h$        | 55.5 | 44.5 | 52.6 |
| $m_A$        | 211.0 | 135.0 | 189.0 |
| $m_H$        | 224.8 | 159.1 | 205.1 |
| $m_{H^+}$    | 225.6 | 156.9 | 205.2 |
| $\alpha$     | $-0.56$ | $-0.69$ | $-0.59$ |
| $m_{\tilde{Z}_1}$ | 13.1 | 13.3 | 13.2 |
| $m_{\tilde{Z}_2}$ | 48.2 | 54.7 | 50.5 |
| $m_{\tilde{Z}_3}$ | 159.0 | 107.6 | 143.6 |
| $m_{\tilde{Z}_4}$ | 187.3 | 142.6 | 174.2 |
| $m_{\tilde{W}_1}$ | 45.0 | 53.6 | 47.3 |
| $m_{\tilde{W}_2}$ | 184.5 | 138.9 | 171.1 |
| $m_{\tilde{g}}$ | 74.4 | 74.4 | 74.4 |
### Table 2: Branching ratios of top

|        | A   | B   | C   |
|--------|-----|-----|-----|
| $t \rightarrow t_1 Z_1$ | 0.054 | 0.093 | 0.063 |
| $\tilde{t}_1 \tilde{Z}_2$ | 0.049 | 0.130 | 0.056 |
| $\tilde{t}_1 \tilde{g}$ | 0.516 | 0.403 | 0.493 |
| $bW^+$ | 0.381 | 0.374 | 0.388 |

### Table 3: Branching ratios of gluino

|        | A   | B   | C   |
|--------|-----|-----|-----|
| $\tilde{g} \rightarrow q\bar{q} Z_1$ | 0.248 | 0.497 | 0.342 |
| $q\bar{q} Z_2$ | 0.022 | 0.011 | 0.021 |
| $q\bar{q} W_1$ | 0.087 | 0.044 | 0.087 |
| $\tilde{t}_1 \tilde{t}_1^* Z_1$ | 0.643 | 0.448 | 0.550 |