

Pair-production and Three-body Decay of the Lighter Stop at the ILC in One-loop Order in the MSSM

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We have been developing a program package called `GRACE/SUSY-1loop` which automatically calculates the MSSM amplitudes in one-loop order. We present numerical results of calculations for pair-production and three-body decay of the lighter stop (\tilde{t}_1) at the International Linear Collider (ILC) using `GRACE/SUSY-1loop`. Since the distributions of missing transverse energy (MET) depend on mass spectrum of SUSY particles, we consider two scenarios on three-body decay of \tilde{t}_1 . In these scenarios, both QCD and EW corrections have positive sign for decay widths and cross sections.

1 Introduction

Supersymmetry (SUSY) between bosons and fermions at the unification-energy scale is considered one of the most promising extension of the standard model (SM) of particle physics. Among the supersymmetric theories, the minimal supersymmetric extension of the SM (MSSM) is a well studied framework of SUSY. Since SUSY is a broken symmetry at the electroweak-energy scale, its relic is expected to remain as a rich spectrum of heavy SUSY particles, which makes calculation of amplitudes very complicated.

For many-body final states, each production process or decay process is described by a large number of Feynman diagrams even in tree-level order. There are still more Feynman diagrams in one-loop order even for two-body final states. For this reason, we have developed the `GRACE` system [1], which enables us to calculate amplitudes automatically. A version of the `GRACE` system called `GRACE/SUSY-1loop` [2] is a program package for automated computations of the MSSM in one-loop order. Other groups independently developed program packages `SloopS` [3] and `FeynArt/Calc` [4] for automatic calculations of the MSSM amplitudes in one-loop order.

Recently, we have calculated radiative corrections of production processes and decay processes of SUSY particles in the framework of the MSSM using `GRACE/SUSY-1loop` [2, 5, 6]. In this paper, we show numerical results of the MET distributions for pair-production and three-body decay of \tilde{t}_1 at the ILC in tree-level order, and also show those of the radiative corrections to cross sections for pair-production [7] and decay widths for three-body decay of \tilde{t}_1 [8, 9] in one-loop order.

2 MET distributions

In the experiments at the Large Hadron Collider (LHC), searches for SUSY particles are performed using an experimental cut on MET as is required to be larger than 100 GeV [10] because of background-events avoidance. When a SUSY particle is heavy and decays directly to a charged particle and the lightest SUSY particle (LSP), e.g. $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$, the MET is expected to be large because the LSP is not observed in detectors and the momentum of the parent particle is small. It, however, can be smaller if a SUSY particle is light and has a large momentum because momenta of particles produced from the decay are boosted along that of the parent particle. Although no light SUSY particle has been observed at the LHC, there is room for it to survive if MET is small.

2.1 Two scenarios

Since the Yukawa coupling of top quark is large, the mass of \tilde{t}_1 can be smaller than that of other squarks. So here we focus on \tilde{t}_1 pair-production $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^*$ and decay at the ILC. To investigate the possibility that $M_{\tilde{t}_1}$ is small enough, we set the mass range of \tilde{t}_1 below the threshold of the two-body decay. Since the MET distributions depend on mass spectrum of SUSY particles, we consider two scenarios for three-body decay of \tilde{t}_1 as follows:

Scenario 1. Large slepton masses

The major decay mode is $\tilde{t}_1 \rightarrow bW^+\tilde{\chi}_1^0$ [5, 6], and its branching ratio is nearly 100% if the mass range of \tilde{t}_1 is between the threshold of the three-body decay, $M_{\tilde{t}_1} = 279$ GeV and the lowest threshold of the two-body decay, which is for the mode $\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$, $M_{\tilde{t}_1} = 368$ GeV.

Scenario 2. Small slepton masses

‘Semi-Leptonic’ decay modes, $\tilde{t}_1 \rightarrow bl^+\tilde{\nu}_l$ and $\tilde{t}_1 \rightarrow b\tilde{l}^+\nu_l$ ($l = e, \mu, \tau$), dominate, and the branching ratio of the mode $\tilde{t}_1 \rightarrow bW^+\tilde{\chi}_1^0$ is negligible small due to the small phase space. The lowest threshold of the two-body decay, which is for the mode $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^+$, is $M_{\tilde{t}_1} = 298$ GeV.

We set SUSY parameters for these scenarios as in Table 1.

Scenario 1				Scenario 2			
$\tan \beta$	10	$M_{\tilde{t}_1}$	<i>variable</i>	$\tan \beta$	7	$M_{\tilde{t}_1}$	<i>variable</i>
μ	-750 GeV	$M_{\tilde{t}_2}$	480 GeV	μ	-500 GeV	$M_{\tilde{t}_2}$	600 GeV
M_2	400 GeV	θ_t	0.8π	M_2	300 GeV	θ_t	0.8π
$M_{\tilde{t}_1^+}$	325 GeV	$M_{\tilde{b}_1}$	330 GeV	$M_{\tilde{t}_1^+}$	170 GeV	$M_{\tilde{b}_1}$	330 GeV
$M_{\tilde{t}_2^+}$	370 GeV	θ_b	0.6π	$M_{\tilde{t}_2^+}$	175 GeV	θ_b	0.6π
$\theta_{e,\mu}$	0.05π	M_A	525 GeV	$\theta_{e,\mu}$	0.01π	M_A	300 GeV
θ_τ	0.2π	$M_{\tilde{g}}$	1389 GeV	θ_τ	0.2π	$M_{\tilde{g}}$	1042 GeV
$M_{\tilde{\nu}_{e,\mu}}$	316 GeV	$M_{\tilde{\chi}_1^0}$	194 GeV	$M_{\tilde{\nu}_{e,\mu}}$	151 GeV	$M_{\tilde{\chi}_1^0}$	146 GeV
$M_{\tilde{\nu}_\tau}$	328 GeV	$M_{\tilde{\chi}_1^+}$	396 GeV	$M_{\tilde{\nu}_\tau}$	152 GeV	$M_{\tilde{\chi}_1^+}$	294 GeV

Table 1: SUSY parameters for two scenarios.

2.2 Numerical results of MET in tree-level order

In Scenario 1, $BR(\tilde{t}_1 \rightarrow bW^+\tilde{\chi}_1^0) \simeq 1$ in the range of $M_{\tilde{t}_1}$ for which three-body decay of \tilde{t}_1 is dominant as studied in [5, 6]. In Scenario 2, however, there are several ‘Semi-Leptonic’ decay modes. Figure 1 shows numerical results of $M_{\tilde{t}_1}$ dependence of branching ratios for three-body decay of \tilde{t}_1 in tree-level order according to Scenario 2.

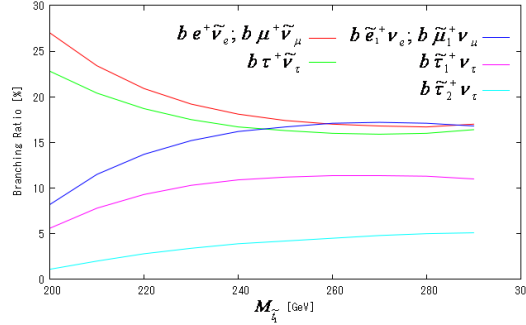


Figure 1: $M_{\tilde{t}_1}$ dependence of branching ratios for three-body decay of \tilde{t}_1 in tree-level order according to Scenario 2.

Figure 2 shows numerical results of (a) MET distributions for $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^* \rightarrow (bW^+\tilde{\chi}_1^0) + (\bar{b}W^-\tilde{\chi}_1^0)$ according to Scenario 1 and (b) those for $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^* \rightarrow (be^+\tilde{\nu}_e) + (\bar{b}e^-\tilde{\nu}_e)$ according to Scenario 2, respectively, at $\sqrt{s} = 1$ TeV in tree-level order. In our calculations, events are generated by SPRING [11] which is a built-in package in the GRACE system. In Scenario 1, the MET is calculated for the two LSP’s. In Scenario 2, a major decay mode $\tilde{t}_1 \rightarrow be^+\tilde{\nu}_e$ is selected, and the MET is calculated for the two sneutrinos.

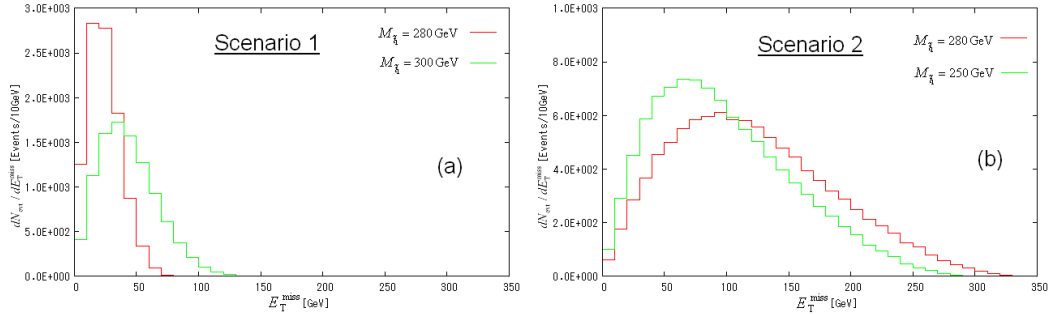


Figure 2: MET distributions at $\sqrt{s} = 1$ TeV in tree-level order. (a) for $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^* \rightarrow (bW^+\tilde{\chi}_1^0) + (\bar{b}W^-\tilde{\chi}_1^0)$ according to Scenario 1; and (b) for $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^* \rightarrow (be^+\tilde{\nu}_e) + (\bar{b}e^-\tilde{\nu}_e)$ according to Scenario 2. Red lines indicate $M_{\tilde{t}_1} = 280$ GeV. Green lines in (a) and (b) indicate $M_{\tilde{t}_1} = 300$ GeV and 250 GeV, respectively.

We should note that the MET in Scenario 1 is small because the difference of numerical values between $M_{\tilde{t}_1}$ and the sum of M_W and $M_{\tilde{\chi}_1^0}$ is small. Although each W boson decays to a pair of quarks or that of a charged lepton and a neutrino, resultant MET distributions

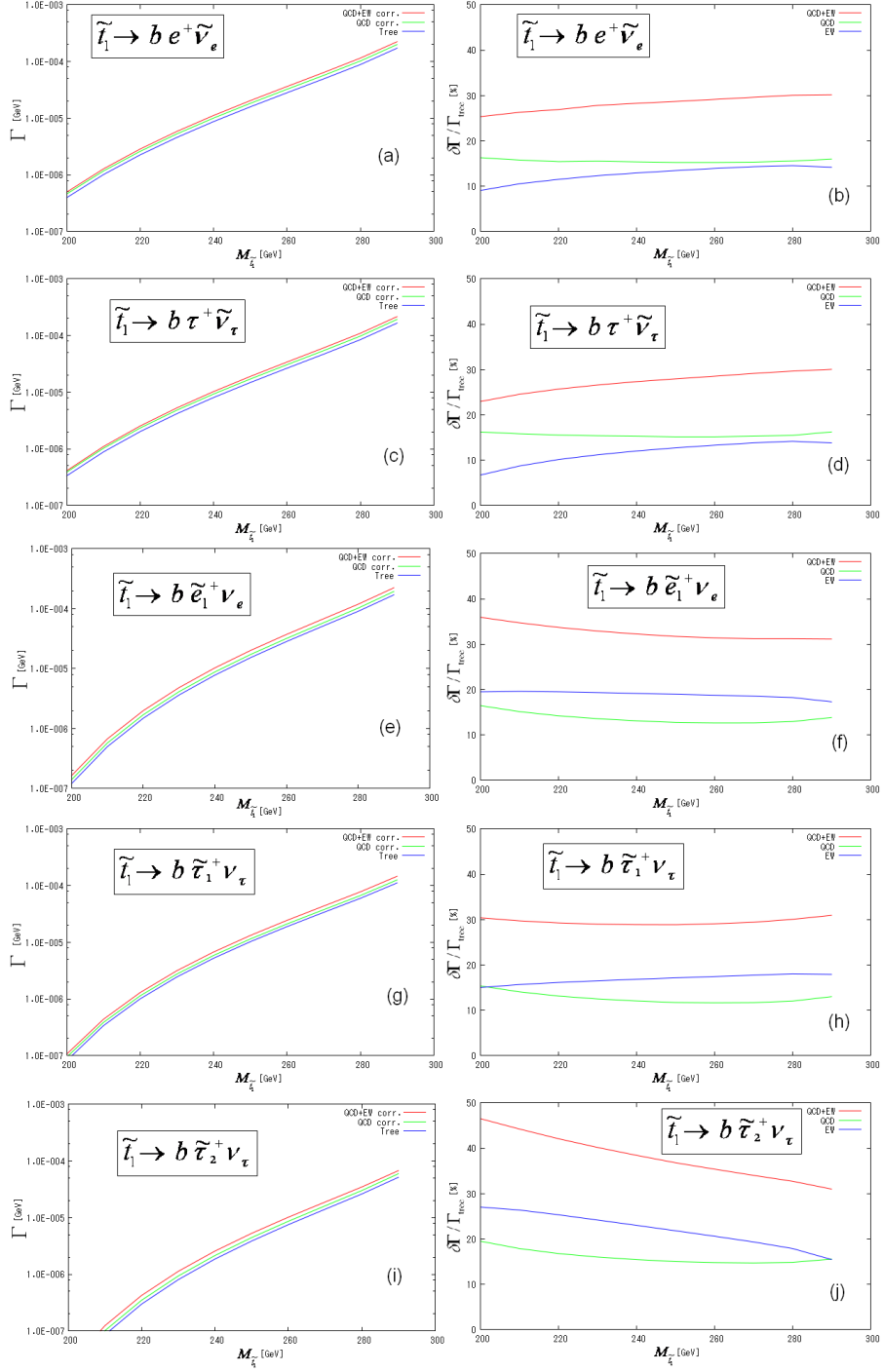


Figure 3: $M_{\tilde{t}_1}$ dependence of decay widths for three-body decay processes of \tilde{t}_1 and their correction rates according to Scenario 2.

are similar to Figure 2 (a) except for the normalization factors because the momenta of the final particles from the W-boson decay are boosted along that of \tilde{t}_1 . It is also notable that the peaks of the MET distributions are less than 100 GeV in Scenario 2.

3 Numerical results of radiative corrections in one-loop order

In Scenario 1, the radiative corrections to decay widths of \tilde{t}_1 in one-loop order have already been studied in [5,6]. In Scenario 2, decay widths for several ‘Semi-Leptonic’ decay modes of \tilde{t}_1 are in the same order. Figure 3 shows numerical results of $M_{\tilde{t}_1}$ dependence of decay widths of \tilde{t}_1 and their correction rates according to Scenario 2. For the decay modes $\tilde{t}_1 \rightarrow bl^+\tilde{\nu}_l$ [(a) - (d) in Figure 3], $\delta\Gamma_{\text{QCD}} > \delta\Gamma_{\text{EW}} > 0$, and for the decay modes $\tilde{t}_1 \rightarrow b\tilde{l}^+\nu_l$ [(e) - (j) in Figure 3], $\delta\Gamma_{\text{EW}} > \delta\Gamma_{\text{QCD}} > 0$. The difference in the behavior of $\delta\Gamma_{\text{EW}}$ between the two is due to that of the QED corrections. Each decay width is enhanced by the total radiative correction in one-loop order.

Figure 4 shows numerical results of $M_{\tilde{t}_1}$ dependence of branching ratios for three-body decay of \tilde{t}_1 in one-loop order according to Scenario 2. The results are similar to those in tree-level order (Figure 1) because $\delta\Gamma$'s of the decay modes are in the same order.

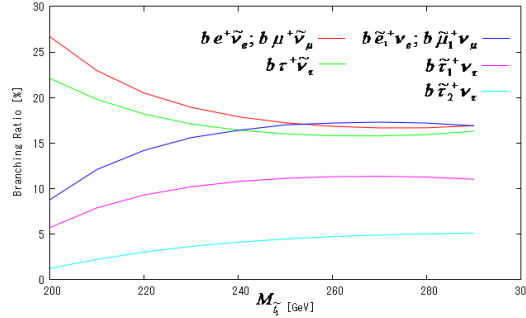


Figure 4: $M_{\tilde{t}_1}$ dependence of branching ratios for three-body decay of \tilde{t}_1 in one-loop order according to Scenario 2.

Figure 5 shows numerical results of (a) $M_{\tilde{t}_1}$ dependence of cross sections for the \tilde{t}_1 -pair production and succeeding decay process, $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^* \rightarrow (bW^+\tilde{\chi}_1^0) + (\bar{b}W^-\tilde{\chi}_1^0) \rightarrow (be^+\nu_e\tilde{\chi}_1^0) + (\bar{b}e^-\bar{\nu}_e\tilde{\chi}_1^0)$ according to Scenario 1 and (b) that for the \tilde{t}_1 -pair production and succeeding decay process, $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^* \rightarrow (be^+\tilde{\nu}_e) + (\bar{b}e^-\tilde{\nu}_e)$, according to Scenario 2 at $\sqrt{s} = 1$ TeV. For comparison, a decay mode $W^+ \rightarrow e^+\tilde{\nu}_e$ is selected in Scenario 1, and a decay mode $\tilde{t}_1 \rightarrow be^+\tilde{\nu}_e$ is selected in Scenario 2. In both scenarios, $\delta\sigma_{\text{QCD}} > \delta\sigma_{\text{EW}} > 0$, and cross sections are enhanced by the total radiative corrections in one-loop order.

We should note that the MET distributions in one-loop order are similar to those in tree-level order except for the normalization factors, and that the MET distributions in the two scenarios can be distinguished by the $b\bar{b}e^-e^+$ tagging.

4 Summary

We have calculated the MET distributions for the pair-production and three-body decay of \tilde{t}_1 in tree-level order, and also calculated the radiative corrections in one-loop order of the

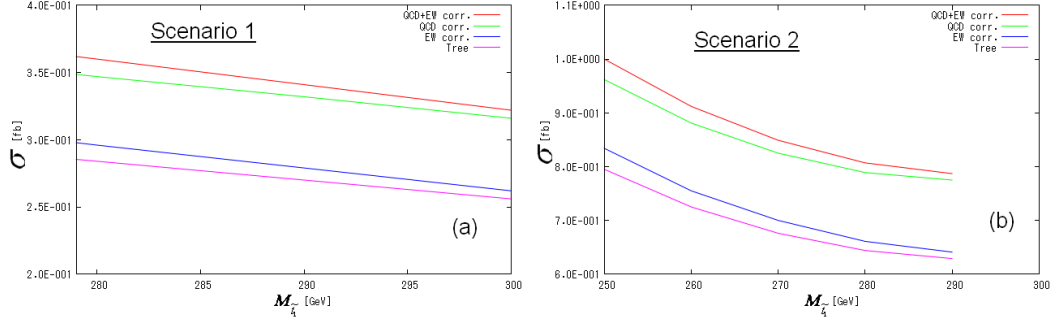


Figure 5: $M_{\tilde{t}_1}$ dependence of cross sections at $\sqrt{s} = 1$ TeV. (a) for $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^* \rightarrow (bW^+ \tilde{\chi}_1^0) + (\bar{b}W^- \tilde{\chi}_1^0) \rightarrow (be^+ \nu_e \tilde{\chi}_1^0) + (\bar{b}e^- \bar{\nu}_e \tilde{\chi}_1^0)$ according to Scenario 1; and (b) for $e^- + e^+ \rightarrow \tilde{t}_1 + \tilde{t}_1^* \rightarrow (be^+ \tilde{\nu}_e) + (\bar{b}e^- \tilde{\nu}_e^*)$ according to Scenario 2.

MSSM for two scenarios on slepton masses. We found that the peak of the MET distributions can be less than 100 GeV if $M_{\tilde{t}_1} \leq 300$ GeV in both scenarios, so events for MET < 100 GeV should be also analyzed in detail for ILC study. In the two scenarios, both QCD and EW corrections in one-loop order have positive sign for decay widths and cross sections in the range of $M_{\tilde{t}_1}$ for which three-body decay of \tilde{t}_1 is dominant.

Acknowledgments

This work was supported in part by Grant-in-Aid for Scientific Research (B)(20340063) and (C)(23540328).

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