Precision Measurements in the Scalar Top Sector of the MSSM at a Linear $e^+e^-$ Collider

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Abstract

The scalar top discovery potential has been studied for the TESLA project with a full-statistics background simulation at $\sqrt{s} = 500$ GeV and $\mathcal{L} = 500$ fb$^{-1}$. The beam polarization is very important to measure the scalar top mixing angle and to determine its mass. The latest estimation of the beam polarization parameters is applied. This study includes $e^+$ polarization, which improves the sensitivity. For a 180 GeV scalar top at minimum production cross section, we obtain $\Delta m = 0.8$ GeV and $\Delta \cos \theta_{\tilde{t}} = 0.008$ in the neutralino channel, and $\Delta m = 0.5$ GeV and $\Delta \cos \theta_{\tilde{t}} = 0.004$ in the chargino channel. The MSSM parameters for the Snowmass point 5 at $\cos \theta_{\tilde{t}} = 0.513$ predict a scalar top of 210 GeV and a neutralino of about 120 GeV. For this parameter choice $\Delta m = 0.95$ GeV and $\Delta \cos \theta_{\tilde{t}} = 0.0125$ is obtained, and a preliminary c-tagging study is presented in the neutralino channel.

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SECTOR OF THE MSSM AT A LINEAR $e^+e^-$ COLLIDER

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with a full-statistics background simulation at $\sqrt{s} = 500$ GeV and $L = 500$ fb$^{-1}$.
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Introduction
The study of the scalar top quarks is of particular interest, since the lighter stop mass
eigenstate is likely to be the lightest scalar quark in a supersymmetric theory. The
mass eigenstates are $m_{\tilde{t}_1}$ and $m_{\tilde{t}_2}$ with $m_{\tilde{t}_1} < m_{\tilde{t}_2}$, where $\tilde{t}_1 = \cos \theta_{\tilde{t}} \tilde{t}_L + \sin \theta_{\tilde{t}} \tilde{t}_R$ and
$\tilde{t}_2 = -\sin \theta_{\tilde{t}} \tilde{t}_L + \cos \theta_{\tilde{t}} \tilde{t}_R$ with the mixing angle $\cos \theta_{\tilde{t}}$. We study the experimental
possibilities to determine $m_{\tilde{t}_1}$ and $\cos \theta_{\tilde{t}}$ at a high-luminosity $e^+e^-$ linear collider
such as the TESLA project [1] with polarized $e^+$ and $e^-$ beams.

The simulated production process is $e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1$ with two decay modes $\tilde{t}_1 \rightarrow \tilde{\chi}^0 c$
and $\tilde{t}_1 \rightarrow \tilde{\chi}^+ b$. A 100% branching fraction in each decay mode is simulated. The
first scalar top decay into a $c$-quark and the lightest neutralino results in a signature
of two jets and large missing energy. The second investigated stop decay mode leads

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also to large missing energy and further jets from the chargino decay. The neutralino channel is dominant unless the decay into a chargino is kinematically allowed. Details of the event simulation with SGV [2] tuned for a TESLA detector [1] are given in Ref. [3]. The signals and a total of 16 million Standard Model background events are simulated (Table 1) for $\mathcal{L} = 500$ fb$^{-1}$.

| Channel | $\tilde{\chi}^0\tilde{c}\tilde{c}$ | $\tilde{\chi}^{+}\tilde{b}\tilde{b}$ | eW$\nu$ | WW | q\bar{q} | $t\bar{t}$ | ZZ | eeZ |
|---------|---------------------------------|---------------------------------|--------|---|--------|--------|---|-----|
| (in 1000) | 50 | 50 | 2500 | 3500 | 6250 | 350 | 300 | 3000 |

Table 1: Number of simulated signal and background events.

**Neutralino Channel**

The reaction $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{\chi}^0\tilde{c}\tilde{c}$ has been studied for a 180 GeV scalar top and a 100 GeV neutralino. After a preselection, 278377 background events remain [4, 3]. In order to separate the signal from the background, the following selection variables are defined: visible energy, number of jets, thrust value and direction, number of clusters, transverse and parallel momentum imbalance, acoplanarity and invariant mass of two jets [4, 3]. An Iterative Discriminant Analysis (IDA) [5] optimized the selection. For unpolarized beams and 12% efficiency, 400 background events are expected.

The polarization of the $e^+$ and $e^-$ beams at a future linear collider offers the opportunity to enhance or suppress the left- or right-handed couplings of the scalar top signal and to determine mass and mixing angle independently. The production cross section of each background process depends differently on the polarization. It is therefore important for a high-statistics analysis to study the expected background channels individually. The expected cross sections [6, 7] are given in Table 2 for different beam polarization states. The IDA was repeated for $-0.9$ and 0.9 polarization [3] $^1$. We recalculated all background rates for the new machine polarization of $-0.8/0.6$ (left-polarization) and $0.8/-0.6$ (right-polarization) as a function of the signal efficiency [12]. For 12% detection efficiency, 1194 background events are expected leading to $\sigma_{\text{left}} = 81.8 \pm 1.3$ fb, and 208 background events giving $\sigma_{\text{right}} = 76.4 \pm 1.2$ fb, where $\Delta \sigma / \sigma = \sqrt{N_{\text{signal}} + N_{\text{background}} / N_{\text{signal}}}$. 

**Chargino Channel**

The reaction $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow \tilde{\chi}^{\pm}\tilde{b}\tilde{b} \rightarrow \tilde{\chi}^{0}W^+b\tilde{\chi}^{0}W^{-}\tilde{b}$ has been studied with focus on the hadronic W decays for a 180 GeV scalar top, a 150 GeV chargino

$^1$For a polarization of $-0.9$, 95% of the $e^-$ are left-polarized. In the previous analyses [8, 9, 10, 11] it was assumed that only 90% of the $e^-$ were polarized.
Table 2: Signal and background cross sections (pb) from different event generators for $e^{-}$ and $e^{+}$ polarization states ($m_{\tilde{t}_{1}} = 180$ GeV and $\cos \theta_{\tilde{t}} = 0.57$). The Zee cross section is 0.6 pb.

and a 60 GeV neutralino, where the chargino decays 100% into a $W$ boson and a neutralino. A preselection similar to that for the study of the neutralino channel is applied and 209051 background events remain [3]. In order to separate the signal from the background, the following selection variables are defined: visible energy, number of jets, thrust value, number of clusters, transverse and parallel momentum imbalance, and the isolation angle of identified leptons. For an unpolarized beam, the final IDA output variable and the resulting number of background events as a function of the signal efficiency were calculated [12]. For 12% efficiency, only 20 background events are expected. Allowing a background rate of 400 events, as in the neutralino channel, the efficiency is 44%, from which we derive the relative error on the cross section to be 0.75%. In this case the number of expected signal events is much larger than the expected background, thus no separate tuning of the IDA for left- and right-polarization is required. The background is neglected for the determination of mass and mixing angle. Note that the dependence of the background rates on the polarization has to be taken into account for stop masses closer to the kinematic threshold.

**Snowmass Point 5**

At the Snowmass 2001 "Summer Study on the Future of Particle Physics" a consensus was reached about a number of defined mSugra points. One of them is dedicated to a light scalar top [13]. For this point the parameters $m_{0} = 150$ GeV, $m_{1/2} = 300$ GeV, $A_{0} = -1000$, $\tan \beta = 5$ and $\mu > 0$ generate a light scalar top at 210 GeV with a mixing angle of $\cos \theta_{\tilde{t}} = 0.513$ and a neutralino of 121.2 GeV mass (SUSYGEN [14]). The scalar top decays at 100% into $\tilde{\chi}^{0}c$ because the chargino mass is about 10 GeV higher than the scalar top mass. A three-particle decay of the scalar top into $b$-lepton–sneutrino is also excluded because the sneutrino mass is too high. The cross section for the production of a scalar top at 210 GeV and
\[ \cos \theta_t = 0.513 \] is roughly half of that obtained for a 180 GeV scalar top at minimum cross section. As the mass differences between scalar top and neutralino for both scenarios are roughly the same (80 and 90 GeV, respectively) the same Standard Model backgrounds have been taken into account. Thus, only the number of signal events decreases by about a factor of two.

In this detailed scenario light MSSM particles are the 220 GeV scalar top 1, the 121 GeV neutralino 1, the 223 GeV neutralino 2, the 223 GeV chargino 1, and the 114 GeV Higgs bosons. Therefore, possible SUSY background reactions are:

- (1a) \[ e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow Z \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]
- (1b) \[ e^+e^- \rightarrow \ell^+\ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]
- (2a) \[ q\bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow q\bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]
- (2b) \[ q\bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow q\bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]
- (3a) \[ e^+e^- \rightarrow \tilde{\chi}_+^\pm \tilde{\chi}_-^\mp \rightarrow W \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]
- (3b) \[ e^+e^- \rightarrow \ell^+\ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0 \]

Only (1a) has a signature similar to the signal, however, the expected production rate is very small for this channel as \[ \sigma(e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0) = 0.037 \text{ pb} \] and the decay branching ratios are \[ \text{BR}(\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0) = 0.012 \] and \[ \text{BR}(Z \rightarrow q\bar{q}) = 0.70. \] Thus, \[ \sigma(e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow q\bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0) = 0.31 \text{ fb} \] and this background rate is expected to be much smaller than the expected signal rate. Therefore, no significant background from Supersymmetric processes is expected.

### C-tagging with SIMDET-4

The preselection [3] has been applied again on generated signal and background events after the events have passed a new detector simulation (SIMDET-4 [15]) in order to study the c-tagging performance. The vertex simulation is based on the TESLA CCD vertex detector from the LCFI Collaboration [16]. For each of the two reconstructed jets a value between 0 and 1 is assigned according to the likelihood of it being a charm jet. The product of these numbers gives a variable that tags whether the event contains charm quarks or not. After preselection cuts [3] 4841/10k signal, 9450/100k W\( \nu \) and 589/100k q\( \bar{q} \) remain. The production cross sections for no polarization were applied. The preliminary efficiency versus purity is shown in Fig. 2 for the \( \tilde{\chi}_1^0 \tilde{\chi}_1^0 \) channel and the q\( \bar{q} \) and W\( \nu \) background reactions. Purity is defined as the ratio of number of simulated signal events after the selection to all selected events. The c-tagging will further improve the final signal to background ratio and help to distinguish a scalar top signal from other possible Supersymmetric reactions involving jets and missing energy.

### Results

For the neutralino and chargino channels of scalar top quarks, we have determined the expected Standard Model background rates as a function of the signal efficiency.
The total simulated background of about 16 million events is largely reduced, which allows a precision measurement of the scalar top production cross section with a relative error of better than 2\% in the neutralino channel and about 1\% in the chargino channel. Based on experiences gained at LEP, we expect that detection efficiencies for other mass combinations are similar as long as the mass difference between the scalar top and the neutralino is larger than about 20 GeV. Figure 1 shows the corresponding error bands and the error ellipse in the $m_{\tilde{t}_1} - \cos \theta_{\tilde{t}}$ plane for both decay channels for 0.8/0.6 left- and right-polarization of the $e^-/e^+$ beams and a luminosity of 500 fb$^{-1}$ each. The statistical errors are a factor 7 better in the neutralino channel and about a factor 14 better in the chargino channel than reported previously [8, 9, 10, 11], and improve further when in addition $e^+$ polarization is included. Detailed results are given in Table 3. The highest statistical precision is obtained in the chargino channel with an error $\Delta m_{\tilde{t}_1} = 0.4$ GeV for $m_{\tilde{t}_1} = 180$ GeV and $\Delta \cos \theta_{\tilde{t}} = 0.003 \cos \theta_{\tilde{t}} = 0.570$.

Table 3: Expected errors on the scalar top mass and mixing angle from simulations with different luminosity and beam polarization in the neutralino (a) and chargino (b) channels. The 10 fb$^{-1}$ analysis [8, 9, 10, 11] used a sequential event selection; while the 500 fb$^{-1}$ results in the neutralino [4] and chargino [3] channels are based on an IDA. The new result includes $e^+$ polarization.

| $\mathcal{L}$ (fb$^{-1}$) | $e^-$ Pol. | $e^+$ Pol. | (a) $\Delta m_{\tilde{t}_1}$ | $\Delta \cos \theta_{\tilde{t}}$ | (b) $\Delta m_{\tilde{t}_1}$ | $\Delta \cos \theta_{\tilde{t}}$ |
|-----------------|------------|------------|----------------|----------------|----------------|----------------|
| 10              | 0.8        | 0.0        | 7.0            | 0.06           | 7.0            | 0.06           |
| 500             | 0.9        | 0.0        | 1.0            | 0.009          | 0.5            | 0.004          |
| 500             | 0.8        | 0.6        | 0.8            | 0.008          | 0.4            | 0.003          |

Figure 2 shows that the bounds on the scalar top mass at 210 GeV and $\cos \theta_{\tilde{t}} = 0.513$ increase. We obtain $\Delta m_{\tilde{t}_1} = 0.95$ GeV and $\Delta \cos \theta_{\tilde{t}} = 0.0125$. Based on the experience from direct searches at LEP, the systematic errors on the event selection are less than 1\%; precise investigations require the detailed detector layout and a full simulation. The stop generator [17] has been interfaced with the SIMDET [15] simulation to allow an independent test of the detector simulation and related systematic errors. Also with the SIMDET-4 simulation and based on an implemented LCFI CCD detector simulation, a preliminary result of the c-tagging performance is presented. Another uncertainty could arise from the luminosity measurement, the measurement of the polarization, and the theoretical uncertainty of the production cross section. A high-luminosity linear collider with the capability of beam polarization has great potential for precision measurements in the scalar quark sector predicted by Supersymmetric theories.
References

[1] ‘Conceptual Design Report of a 500 GeV e+e− Linear Collider with Integrated X-ray Laser Facility’, DESY 1997-048, ECFA 1997-182.

[2] M. Berggren, http://home.cern.ch/b/berggren/www/sgv.html

[3] M. Berggren, R. Keranen, H. Nowak, A. Sopczak, EPJdirect C7 (2000) 1.

[4] M. Berggren, R. Keranen, H. Nowak, A. Sopczak, Proc. Sitges workshop, April 1999 (World Scientific), p. 347.

[5] T.G.M. Malmgren, E.K. Johansson, Nucl. Instrum. Methods A 403 (1998) 481.

[6] H. Eberl, A. Bartl, W. Majerotto, Nucl. Phys. B 472 (1996) 481; S. Kraml, PhD thesis, hep-ph/9903257.

[7] T. Sjostrand, http://www.thep.lu.se/tf2/staff/torbjoern/LCphysgen.html, and references therein.

[8] A. Bartl, H. Eberl, S. Kraml, W. Majerotto, W. Porod, A. Sopczak, Proc. Morioka workshop (World Scientific), p. 571.

[9] A. Bartl, H. Eberl, S. Kraml, W. Majerotto, W. Porod, A. Sopczak, Proc. ‘e+e− Collisions at TeV Energies: The Physics Potential’, Annecy - Gran Sasso - Hamburg, 1995, DESY 96-123D, p. 385.

[10] A. Bartl, H. Eberl, S. Kraml, W. Majerotto, W. Porod, A. Sopczak, Proc. Frascati - London - Munich - Hamburg workshop, 1996, DESY 97-123E, p. 471.

[11] A. Bartl, H. Eberl, S. Kraml, W. Majerotto, W. Porod, A. Sopczak, Z. Phys. C 76 (1997) 549.

[12] H. Nowak, A. Sopczak, Proc. Chicago workshop, Oct. 2000; hep-ph/0102341.

[13] N. Ghodbane, H.-U. Martyn, LC-TH-2001-079, hep-ph/02011233.

[14] N. Ghodbane, S. Katsanevas, P. Morawitz, E. Perez, SUSYGEN 3, hep-ph/9909499.

[15] M. Pohl, H.J. Schreiber, SIMDET V302, DESY 99-030 (1999), and private communications.

[16] Linear Collider Flavor Identification (LCFI) Collaboration, C. Damerell, et.al.

[17] A. Sopczak, in ‘Physics at LEP2’, CERN 96-01, p. 343.
Figure 1: Error bands and the corresponding error ellipse as a function of $m_{\tilde{t}_1}$ and $\cos \theta_t$ for $\sqrt{s} = 500$ GeV, $L = 500 \text{ fb}^{-1}$, $m_{\tilde{t}_1} = 180$ GeV and $\cos \theta_t = 0.57$. Left: neutralino channel. Right: chargino channel.

Figure 2: Left: Error bands and the corresponding error ellipse as a function of $m_{\tilde{t}_1}$ and $\cos \theta_t$ for $\sqrt{s} = 500$ GeV and $L = 500 \text{ fb}^{-1}$. For both plots $m_{\tilde{t}_1} = 210$ GeV and $\cos \theta_t = 0.513$ are used. Right: $c$-tagging efficiency vs. purity after event preselection and SIMDET-4 detector simulation.