Pair Production of Scalar Top Quarks in Polarized Photon-Photon Collisions at ILC

A. Bartl[a,b*], W. Majerotto[c†], K. Mönig[d‡], A. N. Skachkova[e§], N. B. Skachkov[e¶]

[a] *University of Vienna, Faculty of Physics*
1090 Vienna, Boltzmanngasse 5, Austria
[b] *AHEP Group, Instituto de Fisica Corpuscular - C.S.I.C., Universidad de Valencia*
Edificio Institutos de Investigacion, Apt. 22085, E-46071 Valencia, Spain
[c] *Institute for High Energy Physics (HEPHY Vienna)*
Nikolsdorfergasse 18, A-1050 Vienna, Austria
[d] *DESY*
Platanenallee 6, D-15738 Zeuthen, Germany
[e] *JINR*
Joliot-Curie 6, 141980 Dubna, Moscow region, Russia

Abstract

We study pair production of scalar top quarks (stop, $\tilde{t}_1$) in polarized photon-photon collisions with the subsequent decay of the top squarks into b-quarks and charginos $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$. We simulate this process by using PYTHIA6.4 for an electron beam energy $2E^{e}_{beam} = \sqrt{s_{ee}} =$ 1000 GeV. A set of criteria for physical variables is proposed which leads to a good separation of stop signal events from top quark pair production being the main background. These criteria allow us to reconstruct the mass of the top squark provided that the neutralino mass is known.

1 Introduction.

The scalar top quark, the bosonic partner of the top quark, is expected to be the lightest colored supersymmetric (SUSY) [1] particle. $\tilde{t}_L$ and $\tilde{t}_R$, the supersymmetric partners of the left-handed and right-handed top quarks, mix and the resulting two mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$, can have a large mass splitting. It is even possible that the lighter eigenstate $\tilde{t}_1$ could be lighter than the top quark itself [2], [3].

Searches for top squarks were performed at LEP and Tevatron and will continue at LHC and ILC [4], [5]. At ILC it is planned to have the option of a photon collider (PLC), as originally planned for TESLA [6]. This will be achieved by using backscattered photon beams by Compton scattering of laser photon beams with electron beams [7] - [15], (for recent review on this subject see [17]).

It has been stressed that the polarization effects in the interactions of backscattered laser photons [11]–[15] provide additional opportunities for studying the properties of the produced particles (see also [6] and [4], [5]). In the following we study the reaction

$$\gamma + \gamma \to \tilde{t}_1 + \bar{\tilde{t}}_1. \tag{1}$$

*e-mail: alfred.bartl@univie.ac.at
†e-mail: majer@hephy.oeaw.ac.at
‡e-mail: klaus.moenig@desy.de
§e-mail: Anna.Skachkova@cern.ch
¶e-mail: nikskach@gmail.com

Among the possible $\tilde{t}_1$-decay channels within the MSSM (see [18] for details), we focus on the decay $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ followed by the two-body chargino decay $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 W^{\pm}$, where one of the W's decays hadronically, $W \to q_i \bar{q}_j$, and the other one leptonically, $W \to \mu\nu_\mu$ [19] [1]. The final state of this signal process, shown in the left plot of Fig.1, contains two b-quarks and two quarks (originating from thedecay of one W boson), a hard muon plus a neutrino (from the decay of the other W) and two neutralinos:

$$\gamma\gamma \to \tilde{t}_1 \bar{\tilde{t}}_1 \to b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \to b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \to b\bar{b}q_i\bar{q}_j\mu\nu_\mu\tilde{\chi}_1^0\tilde{\chi}_1^0. \quad (2)$$

The main background process is top quark pair production with the subsequent decay $t \to bW^{\pm}$ (for W's we use the same decay channels as in the stop case):

$$\gamma\gamma \to t\bar{t} \to b\bar{b}W^+W^- \to b\bar{b}q_i\bar{q}_j\mu\nu_\mu. \quad (3)$$

The only difference between the final states of stop and top production (shown in the right diagram of Fig.1) is that the stop pair production has two neutralinos which are undetectable. Thus, both processes have the same signature: two b-jets, two jets from W decay and a muon. In the following we show that the physical variables constructed out of the final state may us allow to reconstruct the scalar top quark mass. In the present paper we consider only top pair production as background.

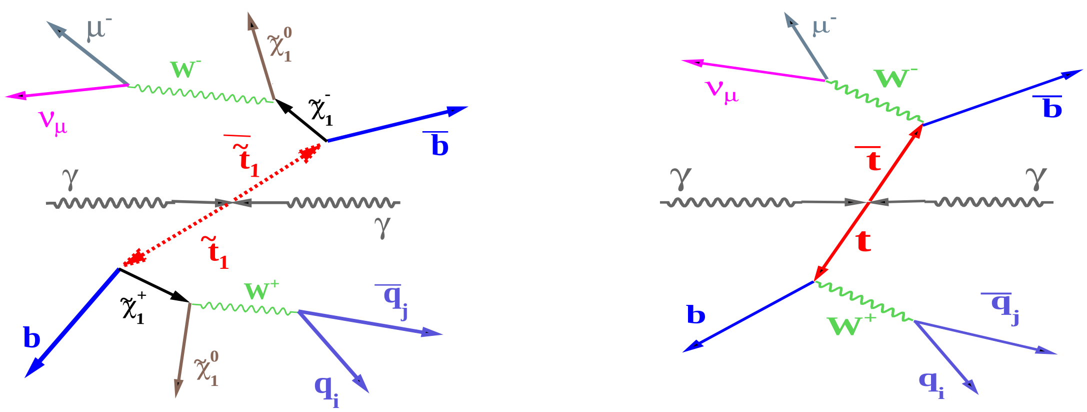

Figure 1: *Left is the stop signal event diagram, Right is the top background diagram.*

We analyse the processes (2) and (3) with the help of Monte Carlo samples of the corresponding events. Two programs PYTHIA6.4 [25] and CIRCE2 [26] were used. To simulate stop pair production process (1), we used the PYTHIA6.4 event generator in which the formula for the cross section of the stop pair production in e^+e^- annihilation was replaced by the formula for two scalar particles (s) production $\gamma\gamma \to s\bar{s}$ from [27], [28], [16], (see [29] for the NLO corrections and [30] for more details about differential cross sections), which takes into account various photon polarization states. The top background was also simulated with PYTHIA6.4. The program CIRCE2 was used to generate the momentum spectra of the backscattered photons involved in the process (1). The energy of the electron beams was chosen to be $E^e_{beam} =$ 500 GeV (i.e. the total e^-e^- energy is $E^{tot}_{e-e-} = \sqrt{s_{ee}} = 1000$ GeV).

In Section 2 we give the set of MSSM parameters used in our study.

In Section 3 the important backscattered photon beam characteristics, namely, momentum spectra and luminosity, are considered for the case of polarized photon production in Compton scattering of polarized laser photons and polarized electrons.

[1] The process $e^+e^- \to \tilde{t}_1 \bar{\tilde{t}}_1$ with the subsequent decay channels $\tilde{t} \to c\tilde{\chi}^0$ and $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ were considered in [20] -[22] and [23], [24], respectively.

In Section 4 we discuss some general characteristics of the signal process $\gamma\gamma \to \tilde{t}_1\bar{\tilde{t}}_1$ and the main background $\gamma\gamma \to t\bar{t}$. The subsections include kinematical distributions for the produced stop quarks, for the jets originating from W boson decay and for b-jets. We compare them in detail with those of top pair production. Subsection 4.2 also deals with the reconstruction of the invariant mass of the two-quark system stemming from the W boson decay as well as with the reconstruction of the invariant mass of the corresponding two-jet system. Subsection 4.3 contains the energy and transverse momentum spectra and some angular distributions of b-quarks and the corresponding b-jets. In Subsection 4.4 we demonstrate how to discriminate between the signal muons produced in W boson decays and those stemming from hadron decays in the same events.

In Section 5 we show the distributions of the global variables as missing energy, total visible (i.e. detectable) energy, the scalar sum of the transverse momenta of all visible particles in the event and the invariant mass of the final-state hadronic jets plus the signal muon. Two further global variables, the invariant mass of all final-state hadronic jets and the missing mass, are also introduced here. It is shown that they are very useful for the separation of background top events.

In Section 6 we propose three cuts which provide a good signal-to-background ratio (S/B).

Section 7 is devoted to the mass reconstruction of the scalar top quark based on the distribution of the invariant mass of one b-jet and the other two $non-b$-jets (from W decay), provided that the neutralino mass is known.

In Section 8 we show the distributions of the invariant variables described in Section 7 for a stop mass $M_{\tilde{t}_1} = 200$ GeV.

Section 9 contains some conclusions.

2 MSSM parameters and cross section.

The scalar top quark system is described by the mass matrix (in the $\tilde{t}_L - \tilde{t}_R$ basis) [2], [31]

$$\begin{pmatrix} M^2_{\tilde{t}_{LL}} & M^2_{\tilde{t}_{LR}} \\ M^2_{\tilde{t}_{RL}} & M^2_{\tilde{t}_{RR}} \end{pmatrix} \tag{4}$$

with

$$M^2_{\tilde{t}_{LL}} = M^2_{\tilde{Q}} + (\frac{1}{2} - \frac{2}{3} sin^2\Theta_W) cos2\beta M^2_Z + M^2_t, \tag{5}$$

$$M^2_{\tilde{t}_{RR}} = M^2_{\tilde{U}} + \frac{2}{3} sin^2\Theta_W cos2\beta M^2_Z + M^2_t, \tag{6}$$

$$M^2_{\tilde{t}_{RL}} = (M^2_{\tilde{t}_{LR}})^* = M_t(A_t - \mu^* cot\beta). \tag{7}$$

The mass eigenvalues are given by

$$M^2_{\tilde{t}_{1,2}} = \frac{1}{2}\left[(M^2_{\tilde{t}_{LL}} + M^2_{\tilde{t}_{RR}}) \mp \sqrt{(M^2_{\tilde{t}_{LL}} + M^2_{\tilde{t}_{RR}}) + 4|M^2_{\tilde{t}_{LR}}|}\right] \tag{8}$$

with the mixing angle

$$cos\Theta_{\tilde{t}} = \frac{-M^2_{\tilde{t}_{LR}}}{\sqrt{|M^2_{\tilde{t}_{LR}}|^2 + (M^2_{\tilde{t}_1} - M^2_{\tilde{t}_{LL}})^2}} \tag{9}$$

$$sin\Theta_{\tilde{t}} = \frac{M^2_{\tilde{t}_{LL}} - M^2_{\tilde{t}_1}}{\sqrt{|M^2_{\tilde{t}_{LR}}|^2 + (M^2_{\tilde{t}_1} - M^2_{\tilde{t}_{LL}})^2}} \tag{10}$$

In the following we shall consider only one particular choice of the MSSM parameters that are defined, in the notations of PYTHIA6, in the following way:

- $M_{\tilde{Q}} = 270$ GeV;
- $M_{\tilde{U}} = 270$ GeV;
- $A_t = -500$ GeV (top trilinear coupling);
- $tan\beta = 5$;
- $\mu = -370$ GeV;
- $M_1 = 80$ GeV;
- $M_2 = 160$ GeV.

Note that in PYTHIA6 $M_{\tilde{Q}}$ corresponds to $M_{\tilde{t}_L}$ (left squark mass for the third generation) and $M_{\tilde{U}}$ corresponds to $M_{\tilde{t}_R}$. These parameters give $M_{\tilde{t}_1} = 167.9$ GeV, $M_{\chi_1^+} = 159.2$ GeV and $M_{\chi_1^0} = 80.9$ GeV. This parameter point is compatible with all experimental data. We have chosen this value of $M_{\tilde{t}_1}$ to be rather close to the mass of the top quark $M_t = 170.9 \pm 1.8$ GeV [32]. Therefore, one expects a rather large contribution from the top background, which means that the choice of this value of the stop mass makes the analysis most difficult. Finding a suitable set of cuts separating stop and top events is therefore crucial.

3 Photon beam characteristics.

Let us mention two main features of photon-photon collisions. The first one is that the monochromaticity of the backscattered photon beam is considerably increased if the mean helicities λ_e and P_c of the electron beam and the laser photon beam are chosen such that $2\lambda_e P_c \approx -1$, as has been shown in [11]-[13] [2]. In this case the relative number of hard photons becomes nearly twice as large in the region of the photon energy fractions $y_i = E_i^\gamma / E_{beam}^e \approx 0.7-0.85$, i = 1, 2, where $E_{1,2}^\gamma$ are the energies of the two backscattered photon beams. Thereby the luminosity in collisions of these photons increases by a factor of 3-4. The growth of backscatterd photon energy spectra in the region of large y_i with the increase of $(-2\lambda_e P_c)$ is illustrated in Fig.3 of [11] and in Fig.2 of [13]. In other words, when $(-\lambda_e P_c)$ increases, the effective "pumping" of soft laser photons into hard backscattered ones increases due to the Compton process. The analogous growth of spectral luminosity $dL_{\gamma\gamma}/dW$ (W is the invariant mass of $\gamma\gamma$ system) in the case when the polarizations in both incoming systems of beam electron and the laser photon satisfy the relation $2\lambda_{1e}P_{1c} = 2\lambda_{2e}P_{2c}$ is demonstrated in Figs.4 of [11] and [13]. As it was mentioned in [11], at $2\lambda_e P_c \approx -1$ the photons with the maximal energy ($y_i \approx 0.7-0.85$) are circular polarized and their helicity is close to $(-P_c)$. Thus, in the limit $2\lambda_{1e}P_{1c} = 2\lambda_{2e}P_{2c} = -1$, the produced pair of most energetic photons have total angular momentum J=0 or J=2, depending on the signs of P_{1c} and P_{2c}. This allows one to measure the cross sections σ_0 and σ_2 which correspond to collisions of $\gamma\gamma$-pairs having total angular momentum 0 or 2, respectively.

The other feature stems from the fact that unlike the situation at an electron-positron collider, the energy of the beams of backscattered photons will vary from event to event. As already mentioned in the Introduction, we use the program CIRCE2 [26] for the energy spectra of the colliding backscattered photons, as well as the values of photon beam luminosities. CIRCE2 uses as input the data files that were generated for TESLA using the code and the set of beam parameters described in [33], [15] and [6] [3]. We use as a reasonable approximation the CIRCE2 output spectra obtained on the basis of the above mentioned data files that were originally generated for $E_{e-e-}^{tot} = 800$ GeV and scale them (by 1000/800) to the higher beam energy $2E_{beam}^e = E_{e^-e^-}^{tot} = 1000$ GeV.

The photon energy spectrum obtained in this way without of any cuts with CIRCE2 for this total energy $E_{e^-e^-}^{tot} = 1000$ GeV is shown in Fig.2 [4]. Two peaks are clearly seen in this

[2] A laser beam polarization of 100% can be assumed. An electron polarization of 85% is expected at the ILC.

[3] The spectra obtained by CIRCE2 are in agreement [34] with the code CAIN [35].

[4] Examples of energy, photon polarization and $\gamma\gamma$ luminosity spectra, obtained for a set of different values of total energy E_{e-e-}^{tot}, can be seen in [10]-[15], [36] and [6].