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Search for a scalar top quark using the OPAL detector

The OPAL Collaboration

Abstract

A search for a supersymmetric partner of the top quark (\tilde{t}_1) has been performed by the OPAL experiment in e^+e^- collisions at LEP. The integrated luminosity of the data sample analysed was 69.1 pb^{-1} , which corresponds to 1.68×10^6 produced $Z^0 \rightarrow q\bar{q}$ events. No \tilde{t}_1 candidates have been found. This study excludes the existence of the \tilde{t}_1 with a mass below 45.1 GeV at 95% C.L., where the mixing angle of left- and right-handed partners is smaller than 0.85 rad or greater than 1.15 rad, and the mass difference between the \tilde{t}_1 and the lightest neutralino is greater than 5 GeV.

(Submitted to Physics Letters B)

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1 Introduction

The scalar top quark (\tilde{t}) can be the lightest charged supersymmetric (SUSY) particle for two reasons [1, 2]. Firstly, one loop radiative corrections to the \tilde{t} mass through Higgsino-quark loops and Higgs-squark loops are always negative. The correction is large for the top quark mass of about 160 GeV, as predicted from the precise measurements of Z^0 parameters at LEP [3], and supported by the recent direct measurement reported by the CDF collaboration [4]. Secondly, the supersymmetric partners of the right-handed and left-handed top quarks (\tilde{t}_L and \tilde{t}_R) mix, and the resultant two mass eigenstates (\tilde{t}_1 and \tilde{t}_2) have a large mass splitting. The lighter mass eigenstate (\tilde{t}_1) can be lighter than any other charged SUSY particle, and lighter than the top quark itself [1, 2]. The \tilde{t}_1 mass can be close to that of the lightest SUSY particle (the neutralino or $\tilde{\chi}_1^0$) for some regions of the allowed parameter space [5]. We assume in this paper that the lightest SUSY particle carries no electric charge and does not interact strongly.

Lower limits on scalar quark masses from $p\bar{p}$ colliders [6] were obtained with the assumptions that all the scalar quark masses of the five or six flavours are degenerate, and that masses of the left and right-handed partners were equal. Such

assumptions are invalid for the \tilde{t}_1 . Furthermore, if the mass difference between \tilde{t}_1 and $\tilde{\chi}_1^0$ is below about 40 GeV, missing transverse energy \cancel{E}_T and transverse energy E_T of jets coming from \tilde{t}_1 decays are too small to be distinguished from the background at $p\bar{p}$ colliders. Searches at e^+e^- colliders are sensitive for small \tilde{t}_1 - $\tilde{\chi}_1^0$ mass differences. Scalar quark searches have been made by DELPHI and MARK II [7] at the Z^0 resonance, with the assumption that masses of left-handed and right-handed partners of a quark are equal. This assumption is not valid for the \tilde{t}_1 search. Limits generally valid for the \tilde{t}_1 were obtained at lower centre of mass energies, at PETRA and TRISTAN [8, 9, 10].

In this paper, we report on a direct search for \tilde{t}_1 using the OPAL detector, for the full range of the possible $Z^0\tilde{t}_1\tilde{t}_1$ coupling strength. As described in more detail below, the \tilde{t}_1 and \tilde{t}_1 decay products contain $\tilde{\chi}_1^0$'s which carry away a large fraction of the energy and momentum. As the $\tilde{\chi}_1^0$ is unobservable, the $\tilde{t}_1\tilde{t}_1$ events would be characterized by two jets which are not back-to-back, and by relatively small visible energy.

2 Phenomenology and Simulation of the \tilde{t}_1 Events

2.1 Production and Decay of the \tilde{t}_1

Scalar top pairs could be produced in e^+e^- annihilation via a Z^0 boson or a virtual photon. The total cross section including both the first order QCD and QED corrections [1] has been calculated as a function of the scalar top mass $m_{\tilde{t}_1}$ and the mixing angle θ_{mix} , where θ_{mix} is defined by $\tilde{t}_1 = \tilde{t}_L \cos \theta_{\text{mix}} + \tilde{t}_R \sin \theta_{\text{mix}}$. The coupling between the \tilde{t}_1 and the Z^0 boson depends on the mixing angle which is determined by the top quark mass and the soft SUSY breaking parameters. For θ_{mix} close to 0.98 ($\cos^2 \theta_{\text{mix}} = \frac{4}{3} \sin^2 \theta_W$), \tilde{t}_1 decouples from the Z^0 boson, and $\tilde{t}_1\tilde{t}_1$ can be produced only via a virtual γ ($\sigma \sim \mathcal{O}(1)$ pb). Otherwise, a large cross section of $\mathcal{O}(100)$ pb is expected for θ_{mix} close to $\frac{1}{4}\pi$ (full mixing state). In this analysis the masses of the \tilde{t}_1 and the $\tilde{\chi}_1^0$, and the mixing angle are treated as free parameters. As the spinless \tilde{t}_1 is pair produced through a Z^0 boson or a virtual photon, the angular distribution $d\sigma/d\cos\theta$ is proportional to $\sin^2\theta$, where θ is the polar angle between the \tilde{t}_1 momentum direction and the beam axis.

The \tilde{t}_1 decays into the lightest SUSY particle ($\tilde{\chi}_1^0$) and non-SUSY particles. The flavour changing two body decay $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ would occur via one-loop processes. The decay width of this mode is estimated to be [1]

$$\Gamma(\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0) = (0.3 \sim 3) \times 10^{-10} m_{\tilde{t}_1} \left(1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{t}_1}^2}\right)^2 \quad (1)$$

Three-body decays of the \tilde{t}_1 containing scalar leptons ($\tilde{t}_1 \rightarrow \tilde{\nu}\ell^+b$, $\tilde{t}_1 \rightarrow \tilde{\ell}^+\nu b$) are not considered here, since a light $\tilde{\ell}$ ($m_{\tilde{\ell}} \lesssim 45$ GeV) and a light $\tilde{\nu}$ ($m_{\tilde{\nu}} \lesssim 40$ GeV) have been already excluded [11].

The four-body decay $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0 f_1 \bar{f}_2$ would occur either through the process of $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+ \rightarrow bW^+\tilde{\chi}_1^0$ or $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \rightarrow bW^+\tilde{\chi}_1^0$. The decay width is estimated to be

$$\Gamma(\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0 f_1 \bar{f}_2) \sim \mathcal{O}(10^{-14}) m_{\tilde{t}_1}, \quad (2)$$

for $\tilde{\chi}_1^\pm$ mass of about 50 GeV which is close to the current lower mass limit of 47 GeV given by the LEP experiments [11]. The decay width of the process via a virtual top quark is further suppressed due to the large top quark mass.

Thus the dominant decay mode of the \tilde{t}_1 would be the flavour changing mode, $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$, and this remains true in the region near the kinematical boundary of $m_{\tilde{t}_1} = m_c + m_{\tilde{\chi}_1^0}$, where the four body decay modes containing b -quark and $\tilde{\chi}_1^0$ in the final state are kinematically forbidden because $m_b > m_c$. Therefore, only the $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ mode is considered in this paper. Because the lifetime of the \tilde{t}_1 is much longer than the typical time scale of the hadronisation, the \tilde{t}_1 would hadronise to form a \tilde{t}_1 -hadron before the \tilde{t}_1 decays.

The width of the $\tilde{t}_1\bar{\tilde{t}}_1$ bound state has been calculated to be approximately 80 keV [12, 13]. The threshold for the open \tilde{t}_1 -hadron production is about 0.6 GeV higher than $2m_{\tilde{t}_1}$ [12]. The narrowness of the bound state prevents it from having any observable effects in the open \tilde{t}_1 -hadron production.

2.2 Event Simulation

The Monte Carlo simulation of the production and the decay of \tilde{t}_1 was performed as follows. Events with a $\tilde{t}_1\bar{\tilde{t}}_1$ pair were generated taking into account initial state radiation [14]. The hadronisation process is subsequently performed to produce colourless \tilde{t}_1 -hadrons and other fragment products according to the Lund string fragmentation scheme (JETSET 7.3) [14, 15]. Parameters of the perturbative QCD and fragmentation processes in the model were optimised using event shape distributions of hadronic Z^0 decays measured using OPAL data [16]. The fragmentation of the \tilde{t}_1 was performed using the fragmentation function proposed by Peterson *et al.* [14, 17], where the parameter $\epsilon_{\tilde{t}_1}$ is set to be

$$\epsilon_{\tilde{t}_1} = \epsilon_b \frac{m_b^2}{m_{\tilde{t}_1}^2}, \quad (\epsilon_b = 0.0057, m_b = 5 \text{ GeV}). \quad (3)$$

The \tilde{t}_1 -hadron is composed of a \tilde{t}_1 and a spectator quark or a diquark. The \tilde{t}_1 decays to a charm quark and a $\tilde{\chi}_1^0$. A colour force string was stretched between the charm quark and the spectator. This colour singlet system was hadronised in the manner of the Lund scheme [14, 15]. Gluon bremsstrahlung (QCD parton showering) was allowed in this process. The generated events were processed by the full detector simulation program and were reconstructed with the same program as the data.

3 The OPAL Detector

The OPAL detector, which is described in detail in [19], is a solenoidal detector with a pressurised central tracking system operating in a 0.435 T magnetic field. A lead-glass electromagnetic calorimeter together with presamplers and time-of-flight scintillators is located outside the magnet coil and pressure vessel. The magnet return yoke is instrumented for hadron calorimetry and is surrounded by external muon chambers. Calorimeters close to the beam axis measure luminosity and complete the acceptance.

A right-handed coordinate system is adopted, where the x -axis points to the center of the LEP ring, and positive z is along the electron beam direction. The angles θ and ϕ are the polar and azimuthal angles, respectively. The detector features of relevance to this analysis are described briefly below.

The central tracking system consists of a vertex drift chamber, a jet chamber, z -chambers and a silicon micro-vertex detector. In the range $|\cos\theta| < 0.73$, 159 points are measured in the jet chamber along each track and at least 20 points on a track are obtained over 96% of the full solid angle.

The forward detectors (FD) are lead-scintillator sandwich calorimeters 24 radiation lengths deep. They are located on both sides of the interaction point and cover the polar angle region between 39 and 150 mrad. In 1993 new silicon tungsten calorimeters (SW) are installed in the polar angle region between 26 and 59 mrad.

The electromagnetic calorimeter (EM) consists of a cylindrical array of 9440 lead-glass blocks of 24.6 radiation lengths thickness (for the barrel), and 2264 lead-glass blocks of 20 radiation lengths thickness (for the end-cap). With excellent hermeticity, these detectors cover the full azimuthal angular range in the polar angle range of $|\cos\theta| < 0.82$ for the barrel and $0.81 < |\cos\theta| < 0.984$ for the endcaps. The barrel lead-glass blocks have a pointing geometry. To achieve good hermeticity, the small 1 mm gaps between the lead-glass blocks do not point exactly to the interaction point. The hermeticity of the endcap calorimeter is due to its non-pointing geometry.

The hadron calorimeter is made up of three sections: the barrel, the endcap and the pole tip, which together cover the region $|\cos\theta| < 0.99$. The magnet return yoke is instrumented with limited streamer tubes in the barrel and endcap sections, and with thin, high gain chambers in the pole tips. There are nine layers of chambers in the barrel, eight in the endcap, and ten in the pole tips. These are read out with narrow strips, and by pads which are grouped together to form towers. The strips are used for tracking, and for muon identification. The towers are used for energy measurement, for which the resolution is $\sigma/E = 120\%/\sqrt{E}$ (E in GeV).

There are at least seven, and in most regions eight, absorption lengths of

material between the interaction point and the muon detectors. Muons with momenta above 3 GeV, usually penetrate to the muon chambers. The muon barrel detector covers the region $|\cos\theta| < 0.7$. It is composed of four layers of planar drift chambers, with cylindrical geometry. The muon endcap detector covers the polar angle range $0.67 < |\cos\theta| < 0.98$. It is composed of two planes of limited streamer tube arrays at each end of the detector. The two muon detector subsystems cover 93% of the full solid angle.

4 Event Selection

The present analysis is based on the data which were taken during the period of 1991-1993 at centre of mass energies around the Z^0 peak. The integrated luminosity of the data sample collected was 69.1 pb^{-1} , which corresponds to 1.68×10^6 produced $Z^0 \rightarrow q\bar{q}$ events.

When calculating the event variables such as thrust axis polar angle θ_{thrust} , visible energy E_{vis} etc., the following charged track selection and calorimeter cluster selection were applied.

The quality requirements of charged tracks used in this analysis are the same as in the Z^0 line shape analysis [20]. It was further required that the track contains more than 50% of the possible hits for a track at the given polar angle, if the momentum of the charged track is greater than 1 GeV, and if no cluster in the electromagnetic calorimeter is associated to the track.

The selection of electromagnetic clusters in the EM is given elsewhere [20]. The energy threshold is set to 0.1 GeV for the barrel and 0.2 GeV for the endcaps. In the case where an EM cluster has an associated charged track, the cluster energy exceeding the momentum of the associated charged track is used to avoid double counting. If the energy of an EM cluster is smaller than the momentum of the associated charged track, the cluster is not used.

The hadron calorimeters are important to capture the energy carried by K_L^0 mesons and neutrons. A large momentum-inbalance is occasionally caused by the fluctuation in the energy measurement of clusters in the hadron calorimeter because of the limited energy resolution. Therefore the hadron calorimeters are used only when the missing transverse momentum \cancel{P}_t normalised by the visible energy E_{vis} satisfies the following condition:

$$\frac{\cancel{P}_t(\text{without HC})}{E_{\text{vis}}(\text{without HC})} > \frac{\cancel{P}_t(\text{with HC})}{E_{\text{vis}}(\text{with HC})} .$$

Although this criterion biases the $\tilde{t}_1\bar{\tilde{t}}_1$ event topology towards smaller \cancel{P}_t and hence the selection efficiency is slightly reduced, the high background rejection power of this procedure makes its inclusion in this analysis essential.

The cuts used to reduce the various types of background events (events from two photon processes, Z^0 decays to hadrons and $\tau^+\tau^-$ pairs, four-fermion events and beam-gas interaction events), are described below. The number of events remaining after each selection criterion is listed in Table 1 for data and typical simulated $\tilde{t}_1\bar{\tilde{t}}_1$ events. Table 2 shows the events remaining after successive cuts for the simulated background processes.

1. In order to reject events from two photon processes and events with hard initial state radiation, scattered electrons or positrons as well as initial state photons with transverse momentum of a few GeV are tagged by using FD and SW detectors. The threshold of the cluster energy of FD and SW is set to 1 GeV. Events are rejected if the sum of cluster energies in FD and SW exceeds 2 GeV.
2. The polar angle of the thrust axis of the event was required to be in the region $|\cos \theta_{\text{thrust}}| < 0.7$. This reduces background events from two photon processes and hadronic Z^0 decays.
3. Events were rejected if all the charged tracks of the event fell within the two back-to-back cones of half-angle 35° around the thrust axis, and if one of the cones contains only one charged track and the other one contains three or more tracks. This cut reduces Z^0 decays into a $\tau^+\tau^-$ pair.
4. The number of jets found was required to be two. The LUCLUS algorithm [14], with jet resolution parameter d_{join} set to be $(1.5 + 2.0 \times E_{\text{vis}}/\sqrt{s})$ GeV, was used for the jet finding. The E_{vis} -dependent d_{join} is needed for good jet reconstruction over a wide range of $m_{\tilde{t}_1}$.
5. Both reconstructed jets must have at least two charged particles. This requirement reduces the $\tau^+\tau^-$ background where either τ decays to one charged particle.
6. Events are rejected if the charged multiplicity of one reconstructed jet is between two and six, and the other jet contains only two oppositely charged tracks identified as electrons or muons. This cut removed four-fermion events of the type $\tau^+\tau^-\ell^+\ell^-$ ($\ell = e$ or μ).

In order to maintain a high search efficiency over a wide range of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$, the E_{vis} , $|\cos \theta_{\text{jet}}|$, and θ_{Acop} cuts were optimised separately for light ($m_{\tilde{t}_1} \lesssim 35$ GeV) and heavy ($m_{\tilde{t}_1} \gtrsim 25$ GeV) \tilde{t}_1 searches, where θ_{jet} is the polar angle of the jet closer to the beam axis, and θ_{Acop} is the complement of the angle between the two jets projected onto the plane perpendicular to the beam axis.

7. Events were accepted if they fell into the following regions in the $E_{\text{vis}}-\theta_{\text{Acop}}$ plane:

- $0.15 \leq E_{\text{vis}}/\sqrt{s} \leq 0.5$ for the light \tilde{t}_1 search,

- $0.15 - \theta_{\text{AcoP}}(^{\circ})/2000 \leq E_{\text{vis}}/\sqrt{s}$ for the heavy \tilde{t}_1 search.

8. Events are accepted if they fell into the following regions of the $|\cos \theta_{\text{jet}}| - \theta_{\text{AcoP}}$ plane:

- $|\cos \theta_{\text{jet}}| < 0.75$ and $\theta_{\text{AcoP}} \geq 15^{\circ} + 20^{\circ} \times |\cos \theta_{\text{jet}}|$ for the light \tilde{t}_1 search,
- $|\cos \theta_{\text{jet}}| < 0.75$ and $\theta_{\text{AcoP}} \geq 30^{\circ} + 60^{\circ} \times |\cos \theta_{\text{jet}}|$ for the heavy \tilde{t}_1 search.

Figures 1 and 2 show the last two cuts for the light and heavy \tilde{t}_1 searches, respectively. The figures show scatter plots of $E_{\text{vis}} - \theta_{\text{AcoP}}$ and $|\cos \theta_{\text{jet}}| - \theta_{\text{AcoP}}$ for data, simulated $\tilde{t}_1 \bar{\tilde{t}}_1$ events and for simulated background events (hadronic Z^0 decays [14], $\tau^+ \tau^-$ [21], and two photon processes [22]).

For heavy \tilde{t}_1 , the wider possible mass differences of \tilde{t}_1 and $\tilde{\chi}_1^0$ give rise to a wider range of E_{vis} and a large average acoplanarity angle. The θ_{AcoP} dependent E_{vis} cut for heavy \tilde{t}_1 efficiently reduces the low E_{vis} background from two photon processes, while maintaining the good detection efficiency for heavy \tilde{t}_1 and small $\Delta m (\equiv m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0})$. As the mass of the \tilde{t}_1 decreases, the range of the $\tilde{\chi}_1^0$ transverse momentum from the \tilde{t}_1 flight direction decreases and the average acoplanarity angle decreases, and the range of the visible energy decreases. Furthermore, when $m_{\tilde{t}_1}$ decreases, the variation of the visible energy range with the mass difference becomes even narrower because a large fraction of visible energy is carried by the particles from the hadronisation process of \tilde{t}_1 .

A more rigorous cut on θ_{AcoP} was made in the heavy \tilde{t}_1 search to reduce the number of events from two photon processes which were not eliminated by the mild E_{vis} cut. Although there are no events in the region of large θ_{AcoP} and large $|\cos \theta_{\text{jet}}|$ for light \tilde{t}_1 search, the $|\cos \theta_{\text{jet}}| < 0.75$ cut is maintained due to the proximity of the events from two photon processes to the lower visible energy cut, with high measured acoplanarity angle. The high value of the acoplanarity angle is a mismeasurement due to the loss of particles down to the beam pipe for those events with large $|\cos \theta_{\text{jet}}|$.

After all the selection cuts have been applied, no events remain in the real data or simulated background data samples. The expected numbers of events from background sources calculated by extrapolating the distributions of simulated background events into the search region, were estimated to be less than 0.4 for the searches in both mass regions.

selection	data		\tilde{t}_1 Monte Carlo	
	light	heavy	light	heavy
raw data	6.61×10^6		2000	2000
(1) FD,SW Veto	4.02×10^6		1990	1986
(2) $ \cos \theta_{\text{thrust}} < 0.7$	1.51×10^6		1714	1451
(3) 1- N prong Veto	1.50×10^6		1689	1421
(4) $N_{\text{jet}} = 2$	4.30×10^5		1090	1318
(5) Multiplicity cut	2.70×10^5		1005	1121
(6) 4-fermion veto	2.69×10^5		965	1050
(7) E_{vis} cut	1090	261865	759	1027
(8) $ \cos \theta_{\text{jet}} - \theta_{\text{Acop}}$ cut	0	0	356	450

Table 1: Event selections for the real data and for the typical \tilde{t}_1 Monte Carlo events. The raw data includes a large number of single track events from $e^+e^- \rightarrow e^+e^-e^+e^-$ and events due to interaction of beam and residual gas in the beam pipe.

selection	$Z^0 \rightarrow q\bar{q}$		$Z^0 \rightarrow \tau^+\tau^-$		$\gamma\gamma$ collision	
	light	heavy	light	heavy	light	heavy
raw data	1.68×10^6		1.00×10^5		5.63×10^5	
(1) FD,SW Veto	1.60×10^6		1.00×10^5		2.75×10^5	
(2) $ \cos \theta_{\text{thrust}} < 0.7$	8.17×10^5		2.95×10^4		6.74×10^4	
(3) 1- N prong Veto	8.17×10^5		2.07×10^4		6.73×10^4	
(4) $N_{\text{jet}} = 2$	2.75×10^5		1.86×10^4		9377	
(5) Multiplicity cut	2.75×10^5		1632		5320	
(6) 4-fermion veto	2.73×10^5		1357		4690	
(7) E_{vis} cut	822	2.73×10^5	184	1357	218	242
(8) $ \cos \theta_{\text{jet}} - \theta_{\text{Acop}}$ cut	0	0	0	0	0	0

Table 2: Number of events expected after each cut for simulated events of hadronic Z^0 decay, $Z^0 \rightarrow \tau^+\tau^-$ and for two photon processes normalized to the same luminosity as the data. The large excess of the events in the data before the multiplicity cut (Table 1) is due to events from soft two photon processes like $e^+e^- \rightarrow e^+e^-e^+e^-$ which is not simulated, but the events are eliminated by the multiplicity cut.

5 Systematic Errors and Mass Limits

5.1 Detection Efficiency

The detection efficiency η depends on $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. We generated $\tilde{t}_1\bar{\tilde{t}}_1$ events with full detector simulation for forty-one combinations of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ with emphasis

on the region where the mass difference is small. The efficiency for arbitrary values of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ is estimated by interpolation. The typical efficiency is 20% in the mass region $m_{\tilde{t}_1} \geq 25$ GeV and $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \geq 5$ GeV.

5.2 Systematic Errors

The sources of systematic error on the detection efficiency η are summarised as follows, where the values of relative errors ($|\Delta\eta|/\eta$) are given:

1. Statistical error of the \tilde{t}_1 Monte Carlo Simulation.
2. Fragmentation function for \tilde{t}_1 : The multiplicity and the visible energy of the $\tilde{t}_1\bar{\tilde{t}}_1$ events depend on the fragmentation function of the \tilde{t}_1 . The fragmentation scheme by Peterson *et al.* was used [17], with the fragmentation parameter $\epsilon_{\tilde{t}_1}$ determined by formula (3). The error in $\epsilon_{\tilde{t}_1}$ is propagated from $\frac{\delta\epsilon_b}{\epsilon_b} = {}^{+0.70}_{-0.50}$ [24] and $\frac{\delta m_b}{m_b} = \pm 0.06$. $\tilde{t}_1\bar{\tilde{t}}_1$ pair events were generated and simulated with masses of 10, 20 and 30 GeV with $\epsilon_{\tilde{t}_1}$ varied by one standard deviation. The change in the detection efficiency was found to be 13%, 10% and 5%, respectively, for the three masses. The deviation $\left(\frac{|\Delta\eta|}{\eta}\right)$ depends mainly on $m_{\tilde{t}_1}$. The systematic error due to $\epsilon_{\tilde{t}_1}$ for arbitrary $m_{\tilde{t}_1}$ was estimated by interpolating the above values.

The fragmentation function proposed by Bowler [23] was also used, because the shape of the fragmentation function is very different from that of Peterson *et al.*. The difference in detection efficiency for events using the Bowler fragmentation function and those using the Peterson function was found to be typically 4%. This difference was taken to be the uncertainty due to the parametrization of the \tilde{t}_1 fragmentation function.

3. Fragmentation of charm quark: The systematic error in the efficiency from the uncertainty in the fragmentation parameter of the charm quark (ϵ_c) is estimated to be typically 4% for all combinations of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$ by varying ϵ_c within the range $\frac{\delta\epsilon_c}{\epsilon_c} = \pm 0.4$ [24].
4. Energy scale of calorimeters: The visible energy cut depends on the absolute energy scale of the calorimeters. The efficiencies for the searches were determined after shifting the electromagnetic calorimeter energy scale by $\pm 1\%$, and the hadron calorimeter energy by $\pm 1.2/\sqrt{E(\text{GeV})}$. The relative change in efficiency was 3% for light \tilde{t}_1 search, and 2% for the heavy \tilde{t}_1 search.
5. The systematic error due to the luminosity measurement and the trigger efficiencies are negligible.

In addition to the systematic errors in the efficiency, the error of the theoretical calculation of the $\tilde{t}_1\bar{\tilde{t}}_1$ pair cross section is evaluated to be less than 1%, and the value of 1% is taken as the systematic error.

The systematic errors are considered to be independent, and the total systematic error is calculated as a quadratic sum of the individual errors, and was found to be 8%–15%, depending on $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}_1^0}$. In calculating the mass limits, the detection efficiency is reduced by the total systematic error.

5.3 Mass Limits

The number of $\tilde{t}_1\bar{\tilde{t}}_1$ events that would pass our analysis cuts has been calculated as a function of $m_{\tilde{t}_1}$, $m_{\tilde{\chi}_1^0}$, and θ_{mix} . In the data no events survived the cuts, and the region where more than 3.0 events are expected is excluded at 95% C.L. Figures 3a and 3b show the excluded regions in the $(\theta_{\text{mix}}, m_{\tilde{t}_1})$ plane for the mass difference $\Delta m (\equiv m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}) \geq 2$ GeV, and ≥ 5 GeV, respectively, together with the regions excluded by lower energy experiments [8, 9].

The decay $Z^0 \rightarrow \tilde{t}_1\bar{\tilde{t}}_1$, if kinematically allowed, would contribute to the Z^0 total decay width Γ_Z [1]. The limit of the excess of Γ_Z with 95% C.L. above the Standard Model prediction has been calculated to be $\Delta\Gamma_Z < 26$ MeV from the measured Γ_Z and its experimental error at LEP [3], taking into account the possible deviations in the theoretical prediction due to the uncertainties in the top quark mass, the Higgs boson mass and α_s . The region excluded by the limit on the excess of the Z^0 total decay width is also shown in the figures 3a and 3b.

The numerical mass bounds are listed in Table 3 for three θ_{mix} values. Assuming that Δm is greater than 2.0 GeV, if the \tilde{t}_1 is purely left-handed ($\theta_{\text{mix}} = 0$), the lower mass limit is 41.2 GeV at 95% C.L. For $\theta_{\text{mix}} = \frac{1}{4}\pi$, the mass region from 6.1 GeV to 38.5 GeV, is excluded. For the case where \tilde{t}_1 completely decouples to Z^0 ($\theta_{\text{mix}} = 0.98$), a mass region around 15 GeV is excluded.

excluded $m_{\tilde{t}_1}$ region (GeV)			
θ_{mix} (rad)	$\Delta m \geq 2$ GeV	$\Delta m \geq 3$ GeV	$\Delta m \geq 5$ GeV
0.0	0.0 ~ 41.2	0.0 ~ 44.9	0.0 ~ 46.0
$\frac{1}{4}\pi$	6.1 ~ 38.5	6.0 ~ 41.8	6.0 ~ 45.2
0.98	11.2 ~ 25.5	9.5 ~ 31.5	7.9 ~ 41.2

Table 3: The excluded $m_{\tilde{t}_1}$ region ($\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$) with 95% C.L.

The exclusion zones in the $m_{\tilde{t}_1}$ - $m_{\tilde{\chi}_1^0}$ plane are shown in Figure 4 for various θ_{mix} values. In this figure, it is shown that, for $\Delta m \geq 5$ GeV and the mixing angle being smaller than 0.85 rad or greater than 1.15 rad, the mass region from 6.1 to 45.1 GeV is excluded at 95% C.L. As can be seen from these figures, the OPAL exclusion region contains all of the exclusion regions determined from lower energy experiments, except for a small region at low $m_{\tilde{t}_1}$. In this region the acoplanarity angle of the two jets is small due to the low momentum of the $\tilde{\chi}_1^0$ transverse to the \tilde{t}_1 flight direction and due to large momentum carried by the fragmentation products in the \tilde{t}_1 flight direction.

6 Summary

Pair production of a supersymmetric partner of the top quark has been searched for using the OPAL detector at the CERN e^+e^- collider LEP. No evidence for such events has been found in the data sample taken in 1991-1993 with integrated luminosity of 69.1 pb^{-1} , which corresponds to 1.68×10^6 produced $Z^0 \rightarrow q\bar{q}$ events. The mass limits were obtained with the conservative assumption that only one of the two mass eigenstates of scalar top quarks is observable at LEP. The \tilde{t}_1 mass is excluded below 45.1 GeV at 95% C.L., where the mixing angle of left and right-handed partners is smaller than 0.85 rad or greater than 1.15 rad, and the mass difference between \tilde{t}_1 and the lightest neutralino is greater than 5 GeV.

Acknowledgements:

Sincere thanks are due to K. Hagiwara (KEK) and T. Kon (Seikei Univ.) for useful discussions. It is a pleasure to thank the SL Division for the efficient operation of the LEP accelerator, the precise information on the absolute energy, and their continuing close cooperation with our experimental group. In addition to the support staff at our own institutions we are pleased to acknowledge the Department of Energy, USA, National Science Foundation, USA, Texas National Research Laboratory Commission, USA, Particle Physics and Astronomy Research Council, UK, Natural Sciences and Engineering Research Council, Canada, Fussesfeld Foundation, Israeli Ministry of Energy and Ministry of Science, Minerva Gesellschaft, Japanese Ministry of Education, Science and Culture (the Monbusho) and a grant under the Monbusho International Science Research Program, German Israeli Bi-national Science Foundation (GIF), Direction des Sciences de la Matière du Commissariat à l'Énergie Atomique, France, Bundesministerium für Forschung und Technologie, Germany, National Research Council of Canada, A.P. Sloan Foundation and Junta Nacional de Investigação Científica e Tecnológica, Portugal.

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Figure 1: The plots for the light \tilde{t}_1 search for the data, typical simulated $\tilde{t}_1\bar{\tilde{t}}_1$ events ($m_{\tilde{t}_1} = 20$ GeV, $m_{\tilde{\chi}_1^0} = 10$ GeV), and the simulated background events (events due to hadronic Z^0 decays, Z^0 decays to τ pairs, and two photon collisions). The corresponding cross section of the $\tilde{t}_1\bar{\tilde{t}}_1$ events in these figures is about 30 pb assuming the luminosity of 69.1 pb^{-1} .

(a) The scatter plot of the visible energy E_{vis} and the acoplanarity angle θ_{Acop} before the E_{vis} cut. The events between the two vertical lines are selected by the E_{vis} cut.

(b) The scatter plot of the jet-direction $|\cos \theta_{\text{jet}}|$ and θ_{Acop} after the E_{vis} cut. The line shows the final cuts on θ_{Acop} and $|\cos \theta_{\text{jet}}|$.

Figure 2: The plots for the heavy \tilde{t}_1 search for the data, typical simulated $\tilde{t}_1\bar{\tilde{t}}_1$ events ($m_{\tilde{t}_1} = 42$ GeV, $m_{\tilde{\chi}_1^0} = 32$ GeV), and the simulated background events (events due to hadronic Z^0 decays, Z^0 decays to τ pairs, and two photon collisions). The corresponding cross section of the $\tilde{t}_1\bar{\tilde{t}}_1$ events in these figures is about 30 pb assuming the luminosity of 69.1 pb^{-1} .

(a) The scatter plot of the visible energy E_{vis} and the acoplanarity angle θ_{Acop} before the E_{vis} cut. The events between the two vertical lines are selected by the E_{vis} cut.

(b) The scatter plot of the jet-direction $|\cos \theta_{\text{jet}}|$ and θ_{Acop} after the E_{vis} cut. The line shows the final cuts on θ_{Acop} and $|\cos \theta_{\text{jet}}|$.

Figure 3: The excluded region in the $(\theta_{\text{mix}}, m_{\tilde{t}_1})$ plane at 95% C.L. where the mass difference is assumed to be:

(a) $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \geq 2 \text{ GeV}$,

(b) $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \geq 5 \text{ GeV}$.

The region excluded from the limit on the Z^0 total decay width ($\Delta\Gamma_Z \leq 26 \text{ MeV}$ at 95% C.L.) and limits from previous publications [8, 9] are also shown.

Figure 4: The excluded region in the $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ plane at 95% C.L. where the mixing angle is assumed to be

$\theta_{\text{mix}} \leq 0.85$ or ≥ 1.15 rad (shaded area),

and $\theta_{\text{mix}} \leq 0.97$ or ≥ 0.99 rad (hatched area).

The dashed curve shows the contour of the limits from previous publications [8, 9].