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Search for a Light Scalar Top Squark in e^+e^- Reactions at $E_{\text{c.m.}} = 58$ GeV

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A search has been made for a light scalar top squark ($\tilde{t}_1$), which has remained unexcluded by previous e^+e^- experiments up to the Z^0 pole. By assuming the decay $\tilde{t}_1 \to c + \tilde{Z}_1$ (lightest neutralino), e^+e^- annihilation data at $E_{\text{c.m.}} = 58$ GeV have been analyzed. The number of events comprising large-acoplanarity particle groups is consistent with that expected from known processes. We excluded $\tilde{t}_1$ in the mass range 7.6–28.0 GeV/c^2 and $\tilde{Z}_1$ with a mass very close to the kinematical limit at the 95% C.L.

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Supersymmetry (SUSY) [1] has been considered to be an attractive strategy for extending the standard model (SM). However, nonobservation of the SUSY partners in our previous searches [2] and other experiments [3] has set the lower mass limits on the scalar fermions and gauginos to be around $M_Z/2$ or beyond 100 GeV/c^2. According to the minimal supersymmetric extension of the SM, the situation is quite different concerning the scalar top squark. Since the t quark is much heavier than other quarks and leptons, a large mixing between the scalar partners of the right- and left-handed t quarks [4–6] leads to a large split in the mass eigenstates and the lighter one ($\tilde{t}_1$) can be much lighter than the t quark, even as light as 30 GeV/c^2 or less. Such a light $\tilde{t}_1$ would decay predominantly through a flavor-changing process into the c quark and the lightest neutralino ($\tilde{Z}_1$), since other decays are kinematically forbidden. The coupling of $\tilde{t}_1$ to the Z^0 is predicted to be dependent on the mixing angle (θ_t) of the scalar partners and vanishes at $\theta_t = 0.98$. The sensitivity to $\tilde{t}_1$ in e^+e^- experiments at the Z^0 pole is therefore severely limited; in fact, there remains a large unexplored space, $0.8 \lesssim \theta_t \lesssim 1.2$, in the $(M_{\tilde{t}_1}, \theta_t)$ plane [6]. It is also hard to find a clear signal of $\tilde{t}_1$ in experiments at hadron colliders [7], especially in a case of the massive $\tilde{Z}_1$. Recent studies by the VENUS [8] and TOPAZ [9] groups at the KEK e^+e^- collider TRISTAN on the two-photon process have shown a large excess of charm production over the expectation by the

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quark-parton model (direct process), $\gamma\gamma \to q\bar{q}$, which was suggested by previous experiments [10]. Though the main part of the excess can be explained with the resolved-photon process [11], where partons in a photon interact with the other photon, it has been argued [9] that a part of it might be from pair production of $\tilde{t}_1$ and the subsequent decay, $\tilde{t}_1 \to c + \tilde{Z}_1$. To give a definite answer regarding the existence of $\tilde{t}_1$, another type of analysis is needed, since the statistics of the charm signals are still limited.

The present analysis was performed in a search for the $\tilde{t}_1$ production in e^+e^- annihilation by using multihadron events collected with the VENUS detector at TRISTAN. TRISTAN is the best place, because the c.m. energy around 60 GeV is the highest one at which e^+e^- annihilation predominantly takes place through one-photon annihilation. Thus, a θ_t-independent analysis can be carried out without suffering a large background from Z^0. We assumed the decay $\tilde{t}_1 \to c + \tilde{Z}_1$, and $\tilde{Z}_1$ to be the lightest SUSY particle and imposed R-parity conservation. The signal would therefore appear as a two-jet event with large acoplanarity. However, conventional shape analyses using the thrust axis or jet clustering are not efficient when the mass difference between $\tilde{t}_1$ and $\tilde{Z}_1$ is small. The event shape in this case no longer has a clear jet topology and the large background from two-photon processes is difficult to reject. In the present analysis the particle groups are formed using leading particles and it is required that the deposit energy is dominated by them. The method enabled us to extend significantly the search region. Since $\tilde{t}_1$ couples to a photon with the same strength as the up-type quarks, the production cross section at the lowest-order QED amounts to 1 pb or more for $M_{\tilde{t}_1}$ close to the beam energy. We ignored the Z^0-exchange process in order to obtain θ_t-independent results.

The VENUS detector is a general-purpose magnetic spectrometer. A description of the detector and the trigger condition is given elsewhere [12]. The data used in the analysis were collected at $E_{\rm c.m.} = 58$ GeV and corresponds to an integrated luminosity of 210 pb^{-1}. We selected 68967 multihadronic events by requiring the following conditions: (1) the number of good tracks with $|\cos\theta| < 0.85$ be at least 5 [a good track is defined as the one containing at least 8 axial and 4 slant layers of the central chamber, $|Z_{\rm min}|$ and $|r_{\rm min}|$, which are the minimum distances from the interaction point in the r-ϕ and r-z plane, be less than 0.2 cm and 20 cm, respectively, and the transverse momentum (p_t) be larger than 0.2 GeV/c]; (2) the total calorimeter energy ($E_{\rm cal}$) within $|\cos\theta| < 0.99$ be larger than 3 GeV; (3) the visible energy ($E_{\rm vis}$), which is the sum of the absolute momenta of good tracks and $E_{\rm cal}$, be between 0.1 and 1.1 times $E_{\rm c.m.}$; and (4) the momentum imbalance, defined as $|\sum_i p_{z,i}|/E_{\rm vis}$, be less than 0.6, where $p_{z,i}$ is the momentum component along the beam axis and the sum is taken over all the particles (good tracks and calorimeter clusters). Condition (1) eliminates events with low track multiplicities, such as dilepton productions through QED processes. Conditions (2) and (3) eliminate events with very small $E_{\rm vis}$ mainly coming from two-photon collision, and QED and multihadron events with much larger $E_{\rm vis}$ than that expected for the $\tilde{t}_1$-pair production. The lower cut values for $E_{\rm cal}$ and $E_{\rm vis}$ were set to be significantly lower than those used in our "standard" multihadron selection [12] in order to obtain sufficient sensitivity to $\tilde{t}_1$ when $M_{\tilde{Z}_1}$ is close to $M_{\tilde{t}_1}$. Condition (4) further eliminates events from two-photon collision and beam-gas interaction with large momentum imbalance.

Next, we selected events with two particle groups as follows. Among the good tracks with $|\cos\theta| < 0.6$, the highest momentum one with $|Z_{\rm min}| < 6$ cm was identified as the leading track. The particles within a cone around the leading track with a half angle of 25° were collected to form a leading group. Among the good tracks not belonging to the leading group, satisfying $|Z_{\rm min}| < 6$ cm, $|\cos\theta| < 0.6$ and separated at least 50° from the leading track, the highest momentum track was assigned as the next-leading track. The next-leading group was formed by collecting particles within a cone around the next-leading track with a half angle of 25°. A total of 59075 events were selected. The visible energies ($E_{\rm vis1}$ and $E_{\rm vis2}$) and the summed momentum vectors ($\mathbf{P}_{\rm sum1}$ and $\mathbf{P}_{\rm sum2}$) were calculated from the particles belonging to the leading and the next-to-leading groups. The following conditions were required to the particle groups: (5) the ratio $E_{\rm vis2}/E_{\rm vis1}$ be between 0.2 and 5, (6) the ratio $R_{\rm sum} \equiv (E_{\rm vis1} + E_{\rm vis2})/E_{\rm vis}$ be larger than 0.8, and (7) the acoplanarity angle ($\theta_{\rm acop}$), defined as the supplement of the opening angle between $\mathbf{P}_{\rm sum1}$ and $\mathbf{P}_{\rm sum2}$ projected onto the r-ϕ plane, be larger than 40°. Condition (5) rejects events in which the next-leading group contains only a small part of the hadron fragments due to the limited detector acceptance. Condition (6) is quite effective for eliminating contaminations from two-photon collision since they tend to have a large amount of energy flow at small polar angles. In fact, the number of events satisfying condition (6) is almost unchanged even if the lower cut value in condition (3) is changed from 0.1 to 0.5 times $E_{\rm c.m.}$. Also, multihadron events with hard radiation or multijet topology were rejected. Figure 1(a) shows $R_{\rm sum}$ of the events satisfying condition (5). Most of the events passing through condition (6) are typical two-jet events with back-to-back topology. Figure 2 shows $\theta_{\rm acop}$ of the events satisfying condition (6). By imposing condition (7), a total of 2 events were selected as candidates.

Contamination from one-photon annihilation with existing quark flavors was estimated using the JETSET 7.3 (parton shower) program [13]. Concerning contamination from the two-photon process, the direct and resolved-photon processes were simulated by the PYTHIA 5.6 program [14] with default parameters and connected to JETSET 7.3. The diffractive process was generated based on the generalized vector dominance model (GVDM)

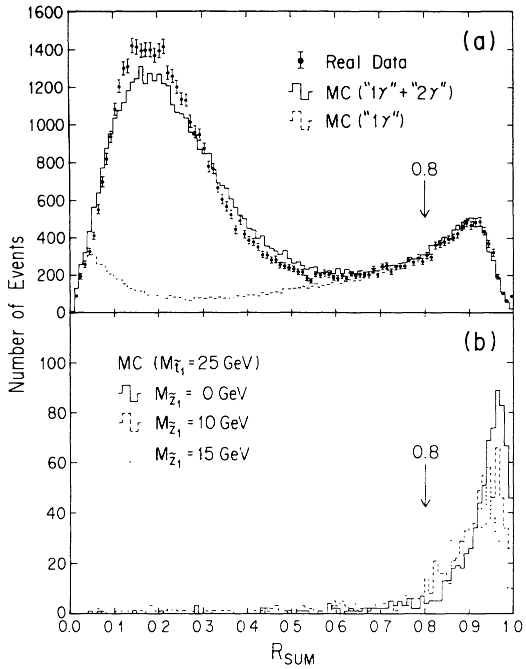

FIG. 1. $R_{\rm sum}$ distribution. (a) Real data (dots) and Monte Carlo (MC) simulation (histograms) for the known processes. "1γ" and "2γ" indicate the one-photon and two-photon (direct + resolved-photon + GVDM) processes, respectively. (b) MC simulation for the $\tilde{t}_1$ production (2000 events).

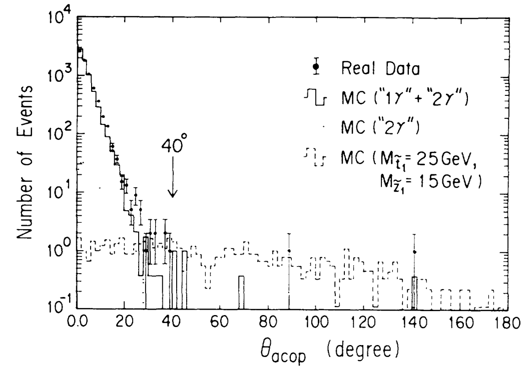

FIG. 2. $\theta_{\rm acop}$ distribution for events with $R_{\rm sum} > 0.8$. Histograms show luminosity-normalized MC simulations for the known processes and the $\tilde{t}_1$ production.

[15]. For the resolved-photon process, parametrizations (DG, LAC1, and GRV [16]) were used for parton components in a photon with a cut value ($p_t^{\rm min}$) on the transverse momenta of the outgoing partons. The data were processed by a program (VMONT) for a full detector simulation and analyzed using the same program as used for the real data. The luminosity-normalized $R_{\rm sum}$ and $\theta_{\rm acop}$ distribution by the simulations, are shown in Figs. 1(a) and 2, respectively, where DG parametrization with $p_t^{\rm min} = 1.6$ GeV/c is used for the resolved-photon process. We can see that the real data are well reproduced by the simulation for the known processes, whose contribution was estimated to be 1.8 ± 1.6 events in the final event sample. Background from beam-gas interaction is ignored, since the average $Z_{\rm min}$ of the good tracks of events passing through condition (6) shows no tails around the interaction point. The error is a combination of the statistical and systematic errors, which are of the same order. We evaluated the systematic error by comparing the results with different parametrizations for parton components in a photon and by changing $p_t^{\rm min}$ up to the level that the cross section of the resolved-photon process changed by a factor of 2 and $E_{\rm vis}$ and $R_{\rm sum}$ distribution could no longer be reproduced. The number of observed events (2) is in good agreement with the estimation. Taking a conservative viewpoint and not subtracting the estimated backgrounds, we set the upper limit on the contribution of unknown process to be 6.3 at the 95% C.L.

A simulation for $\tilde{t}_1$ production and decay was carried out to estimate the detection efficiency for various mass combination of $\tilde{t}_1$ and $\tilde{Z}_1$. The $\tilde{t}_1$ pair was generated with the initial state radiation, and fragmented to form a pair of $\tilde{t}_1$ hadrons before decay, since the lifetime of $\tilde{t}_1$ is estimated to be far longer than the strong-interaction time scale [5]. The JETSET 7.3 program was used for the fragmentation of $\tilde{t}_1$ and the partons based on the LUND symmetric string fragmentation function with default parameters. The generated events were passed through VMONT and analyzed in the same way as the real data. The expected $R_{\rm sum}$ distribution with $M_{\tilde{t}_1} = 25$ GeV/c^2 is shown in Fig. 1(b). Most of the events satisfy condition (6). The luminosity-normalized $\theta_{\rm acop}$ distribution is indicated in Fig. 2, showing a clear difference from the real data. The detection efficiency decreases when the mass difference between $\tilde{t}_1$ and $\tilde{Z}_1$ becomes small; for $M_{\tilde{t}_1} = 28$ GeV/c^2 it is 23% for massless $\tilde{Z}_1$ and 8% for $M_{\tilde{Z}_1} = 20$ GeV/c^2. The obtained mass limits at the 95% C.L. are indicated by a solid curve in Fig. 3. We used the cross section with the initial state radiation and did not include a QCD correction in order to avoid any ambiguity. The limits are conservative, since the QCD correction increases the cross section by up to 30% [6] for most values of $M_{\tilde{t}_1}$. Being much smaller than the QCD correction, we neglected the systematic error (16%), obtained from the quadratic sum of the uncertainties in the fragmentation parameters (12%), simulation of the detector response (10%), luminosity measurement (3%), and trigger inefficiency for hadronic events with small $E_{\rm vis}$ (2%).

The obtained limits exclude $\tilde{t}_1$ in a mass range between 7.6 and 28.0 Gev/c^2 for a massless $\tilde{Z}_1$ and exclude a massive $\tilde{Z}_1$ with a mass very close to (about 1 GeV/c^2 below) the kinematical limit given by the assumed c quark mass (m_c) of 1.5 GeV/c^2. The limits on the nondegenerate SUSY partner ($\tilde{q}_R$) of the right-handed up-type quark from the previous experiments [17] are also presented in

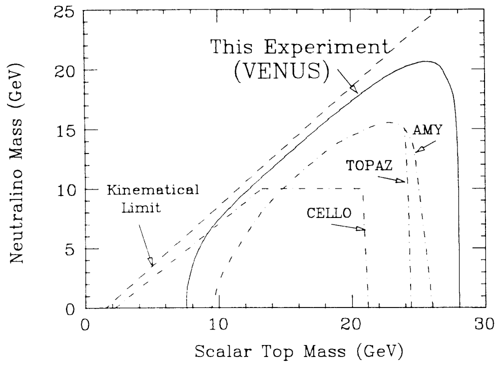

FIG. 3. Excluded mass region for $\tilde{t}_1$ and $\tilde{Z}_1$ at the 95% C.L. The solid curve indicates the present result. The dashed line is the kinematical limit given by $m_c = 1.5$ GeV/c^2. The dot-dashed curves indicate the limits on the scalar quark ($\tilde{q}_R$) from the previous experiments [17].

Fig. 3. Combining the present result with them, we can say that the up-type scalar quark with a mass below 28 GeV/c^2 is excluded except for a narrow region just below the kinematical limit in the $(M_{\tilde{t}_1}, M_{\tilde{Z}_1})$ plane. This imposes a strong constraint on the interpretation of the excess in the c quark production in two-photon collision [9]. We note that the limits on scalar quarks obtained at the CERN e^+e^- collider LEP and the SLAC Linear Collider [18] cannot be applied to $\tilde{t}_1$ due to the θ_t-dependent coupling to Z^0. The present result has excluded large space in the $(\theta_t, M_{\tilde{t}_1})$ plane presented in Fig. 1 of Ref. [6].

In summary, we have searched for $\tilde{t}_1$ production in e^+e^- annihilation at $E_{\text{c.m.}} = 58$ GeV, based on the assumption of the decay $\tilde{t}_1 \to c + \tilde{Z}_1$. From a data sample of 210 pb^{-1} collected with the VENUS detector, we excluded at the 95% C.L. $\tilde{t}_1$ in the mass range between 7.6 and 28.0 GeV/c^2 and $\tilde{Z}_1$ with a mass very close to the kinematical limit.

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