Search for Top Quark in e^+e^- Collisions at $\sqrt{s} = 52$ GeV

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We searched for possible signatures of top-quark production in 508 e^+e^- hadronic annihilation events collected at $\sqrt{s} = 52$ GeV by the TOPAZ detector at the KEK e^+e^- collider TRISTAN. The observed hadronic cross section and shape of hadronic events are consistent with the standard-model predictions without top quarks. A lower limit (95% confidence level) on the mass of the lightest top meson is set at 25.8 GeV.

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The electron-positron annihilation process is the most straightforward means to search for new heavy quarks including the top quark. Previous searches[1] in e^+e^- annihilation have set a lower limit to the mass of the top quark at 23.3 GeV. (To avoid theoretical uncertainty in definition of the top-quark mass, we regard the mass of the lightest top meson as equivalent to the top-quark mass in this Letter.) Although top quarks will decay to lighter quarks and fragment to multiple hadrons, they will leave several clear signatures when produced. One signature is an increase in the total hadronic cross section relative to the pointlike $\mu^+\mu^-$ cross section (the ratio R). The quark-parton model based on quantum chromodynamics (QCD) predicts the ratio R to increase by approximately $\frac{4}{3}$ as the total energy ($\sqrt{s}$) goes past the $t\bar{t}$ threshold. Another signature is the shape of the hadron distribution in momentum space. Hadrons fragmenting from slowly moving top quarks will be distributed spherically, while those from lighter quarks form relatively collinear (two jets) or coplanar (three jets) distributions. We searched for these two signatures among the hadronic annihilation events collected by the TOPAZ detector at the KEK e^+e^- collider TRISTAN. We report here the measured R ratios at $\sqrt{s} = 50$ and 52 GeV and the shape of the observed hadron jets at $\sqrt{s} = 52$ GeV. From these measurements, we set limits to the production cross section and the mass of the top quark.

The TOPAZ detector[2] is a general-purpose detector featuring a time-projection chamber (TPC) as the central tracking device. The detector is shown schematically in Fig. 1, and the components used in the present analysis are listed below:

Inner drift chamber (IDC): A cylindrical drift chamber with ten anode layers. It gave the charged-particle pretrigger in the present experiment.

Time-projection chamber (TPC): It has a fiducial volume of 2.4 m (diameter) × 2.2 m (length), consists of sixteen sectors, each equipped with 10 pad rows and 175 wires, and is filled with Ar/CH$_4$ (90/10) gas at 3.5 atm. The measured position and dE/dx resolutions were $\sigma_{r\phi} = 230\ \mu$m, $\sigma_z = 380\ \mu$m, and $\sigma(dE/dX) = 5.1\%$.

Time-of-flight (TOF) counter: 64 plastic scintillators were used to give the charged-particle pretrigger in this

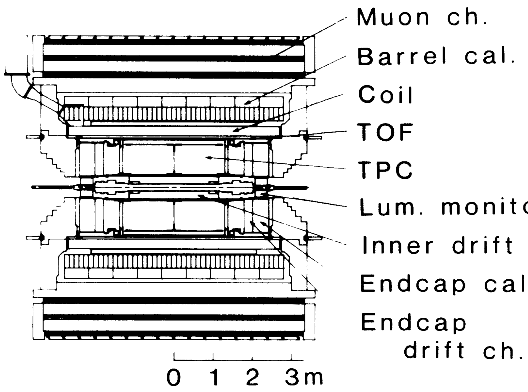

FIG. 1. Cross section of the TOPAZ detector.

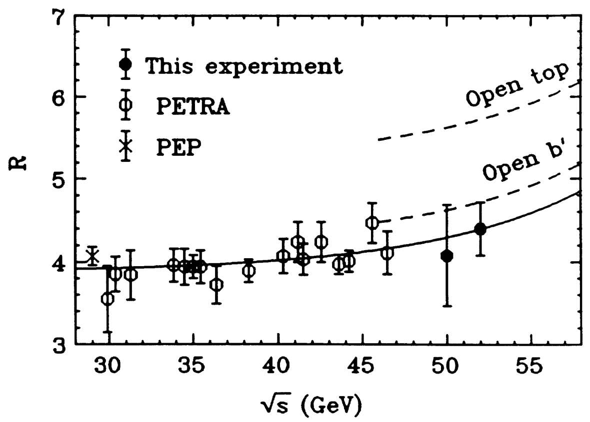

FIG. 2. Ratio R obtained by this experiment and by the previous experiment (Ref. 5). The experimental data by PEP and PETRA were taken from the compilation by Behrend *et al.* (Ref. 6). The solid curve is the standard-model prediction without the top quark for $\sin^2\theta_W = 0.226$ and $\alpha_s(\sqrt{s} = 52\ \text{GeV}) = 0.134$. The dashed curves show the R ratio expected for the addition of the top quark or a new $Q = \frac{1}{3}e$ quark (b').

experiment.

Superconducting coil: It is 2.9 m (diameter)×5.1 m (length)×$0.7X_0$ (thickness) in size, where X_0 denotes 1 radiation length. The magnetic field is 1.0 T.

Barrel calorimeter (BCL): 4300 lead-glass blocks (SF6W, $20X_0$ thick) which covered $30° < \theta < 150°$ and gave energy resolution of $\sigma_E/E = 4.5\%$ for Bhabha events.

End-cap calorimeter (ECL): A Pb-proportional-wire-chamber sandwich ($18X_0$ thick) covering $12° < \theta < 30°$ and gave $\sigma_E/E = 6.7\%$ for Bhabha events.

In the analysis presented here, signals from TPC, BCL, and ECL were primarily used. The momentum resolution for charged particles attained at the time of the analysis was $\sigma_{p_t}/p_t = [(1.6p_t)^2 + 1.6^2]^{1/2}\%$, where p_t is the transverse momentum in GeV/c.

The accelerator was operated at $\sqrt{s} = 50$ and 52 GeV. The effective integrated luminosities were 0.44 pb^{-1} at $\sqrt{s} = 50$ GeV and 3.60 pb^{-1} at $\sqrt{s} = 52$ GeV, which were calculated from the number of Bhabha events observed in the ECL. The following two trigger conditions were relevant to the present analysis: energy trigger, energy deposit > 4 GeV in BCL *or* > 10 GeV in ECL *or* > 4 GeV in both ends of ECL *or* > 1 GeV in two BCL segments (three segments along z in total); track trigger, ≥ 2 charged tracks in IDC and TOF (pretrigger) *and* tracks in both end caps of TPC. The total trigger rate was typically around 2 Hz, which caused a dead-time fraction of less than 5%.

The hadronic events were selected out of the recorded events by the requirement that all the following criteria be satisfied: (i) More than four tracks with $p_t > 0.15$ GeV/c and $|\cos\theta| \leq 0.83$ are extrapolated to the interaction point; (ii) the larger of the invariant masses in two hemispheres ≥ 2.5 GeV; (iii) total visible energy ≥ 20 GeV; (iv) $|\sum p_z/\sum_p| \leq 0.4$; (v) no more than one cluster in BCL or ECL may have energy deposit $> \frac{1}{2}E_{\text{beam}}$. Criteria (ii) and (v) are to remove $\tau\bar{\tau}$ and Bhabha events, and (iii) and (iv) are essential to remove two-photon events. These cuts selected 61 samples ($\sqrt{s} = 50$ GeV) and 508 samples ($\sqrt{s} = 52$ GeV) as candidates for hadronic annihilation events. The contaminations by two-photon, $\tau\bar{\tau}$, and Bhabha events were estimated by Monte Carlo programs to be less than 0.1%, 0.6%, and 0.1%, respectively.

The ratio R is calculated from the observed numbers of hadronic events (N_{obs}) as $R = (N_{\text{obs}} - N_{\text{bkg}})/[L(1+\delta)\eta\sigma^0_{\mu\mu}]$, where N_{bkg} is the estimated background, L is the integrated luminosity, $1+\delta$ is the radiative correction, and η is the detector acceptance. We used the integrated luminosities previously quoted. The radiative correction factor was calculated to be 1.33 by use of the Berends-Kleiss formula[3] where the maximum energy allowed for the initial-state radiation is set as $k_{\max} = 0.99E_{\text{beam}}$. The detector acceptance for the hadronic annihilation event was calculated by Monte Carlo simulations (LUND 6.3 and LUND 5.3)[4] to be 74% for the same $k_{\max}$.

We examine below possible sources of error other than the statistical one in N_{obs}. In the radiative correction, the uncertainty in the effective $k_{\max}$ may introduce error. This is estimated to be 1.5% by the calculation of $(1+\delta)\eta$ for $k_{\max} = 0.8E_{\text{beam}}$ and $0.99E_{\text{beam}}$. We estimated a possible error in the calculation of the detector acceptance by varying the cut parameters and by comparing the results of two programs LUND 5.3 and LUND 6.3. These two tests gave values differing by 2.5% and 4.0%, respectively, for the total acceptance. The uncertainty in the integrated luminosity was estimated to be 4.1% by comparison of the luminosity values obtained by different azimuthal segments of ECL. Adding all these possible errors in quadrature, we get the value quoted below as the systematic error:

$$R = 4.08 \pm 0.53(\text{stat}) \pm 0.28(\text{sys}) \quad (\sqrt{s} = 50\ \text{GeV}),$$

$$R = 4.40 \pm 0.20(\text{stat}) \pm 0.28(\text{sys}) \quad (\sqrt{s} = 52\ \text{GeV}).$$

The present R values are plotted with the previous measurements[5] at the DESY and SLAC storage rings PETRA and PEP in Fig. 2 together with the standard-model predictions with the top quark or with an additional $|Q| = \frac{1}{3}e$ quark. Our measurement is clearly inconsistent with the standard-model prediction with the top quark. However, it cannot rule out an additional $|Q| = \frac{1}{3}e$ quark. The measured R value at $\sqrt{s} = 52$ GeV was compared with the following theoretical cross-section formula near the threshold of $t\bar{t}$ production[7]:

$$\sigma_{t\bar{t}} \propto \tfrac{4}{3}\,[\beta(3-\beta^2)/2] \times (\text{QCD corrections}).$$

Note that β in the equation is the velocity of the top quark and depends on its mass.

The upper limit set for $R < 5.09$ [95% confidence level (C.L.)] at $\sqrt{s} = 52$ GeV can then be converted to a lower limit to the mass of the top meson, $m_T > 24.4$ GeV (95% C.L.). We did not use the nonobservation of the low-lying $t\bar{t}$ resonances in setting the mass limit.

In the shape analysis, we used only the data taken at $\sqrt{s} = 52$ GeV. Prior to the analysis, an additional cut was made on the angle that the sphericity axis made with the beam, $|\cos\theta_{\text{axis}}| < 0.8$. This is to ensure that hadronic jets were well contained in the detector. A total of 448 events survived this cut. To describe the shape of the hadron distribution we used the aplanarity (A) and the thrust (T). Aplanarity is defined as $A = \frac{3}{2}Q_1$, where Q_1 is the smallest eigenvalue of the momentum tensor.[8] Thrust is defined as $T = \text{Max}(\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{n}}| / \sum_i |\mathbf{p}_i|)$ where $\hat{\mathbf{n}}$ is a unit vector. The aplanarity and thrust distributions for the 448 events are shown in Fig. 3 with the predictions of the standard model. The solid and dashed curves are the predictions without and with the top quark ($m_t = 25$ GeV). The number of observed events with $A > 0.08$ was twelve, whereas the Monte Carlo program with and without the top quark ($m_t = 25$ GeV) predicted 26.6 and 11.4 events, respectively. Possible sources of systematic error in the shape analysis are mostly those already discussed in the R measurement. There is, however, one important difference: The shape of the hadron distribution is more dependent on the hadronization process, that is, the Monte Carlo program used to simulate the process. To estimate this dependence, we ran two programs (LUND 5.3 and LUND 6.3) with several sets of fragmentation parameters. Here we assumed that the programs tuned at lower energies[9] work reasonably well at 52 GeV. The number of events varied by about 23% for different sets. The possible error in the measurement was estimated by our combining this with the others listed in the R measurement as 24%. From the number of observed events with $A > 0.08$ the upper limit to the top-quark production was obtained, $\sigma(t\bar{t}) < 8.2$ pb (95% C.L.). By assuming the energy dependence of the cross section near the threshold of $t\bar{t}$ production (see the preceding paragraph), we can set a lower limit to the top-meson mass at 25.8 GeV (95% C.L.).

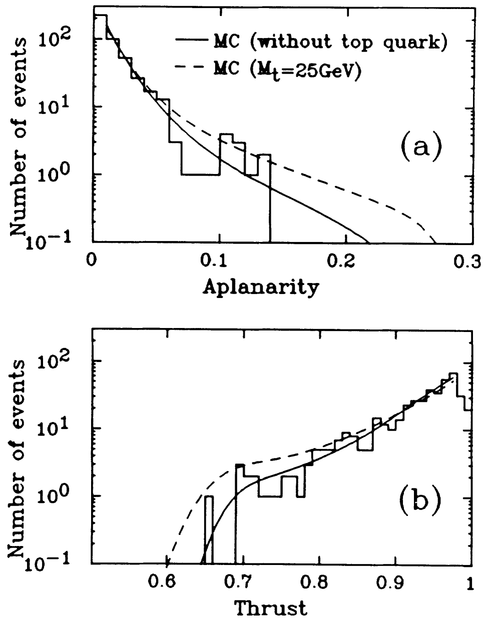

FIG. 3. (a) Aplanarity and (b) thrust distributions obtained from the experiment. The histograms are the observed distributions. The solid and dashed curves are predictions without and with top quarks, respectively.

We conclude that the top quarks are not observed in the e^+e^- annihilation at $\sqrt{s} = 52$ GeV. The measured R ratio and the measured aplanarity distribution set lower limits to the mass of the lightest top meson at 24.4 and 25.8 GeV, respectively. The e^+e^- annihilation channel is probably the simplest and the most studied of reactions used in new-quark searches. The limits obtained here are relatively free from theoretical uncertainties.

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