Search for Sequential Heavy Leptons in e^+e^- Collisions at the Energy $\sqrt{s}=52$ GeV

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A search for sequential heavy leptons has been performed at the center-of-mass energy of 52 GeV at the KEK colliding-beam accelerator TRISTAN. We have found no evidence for the production of heavy leptons with the integrated luminosity of 2.9 pb^{-1}. A lower mass limit of 25.0 GeV/c^2 at 95% confidence level was obtained.

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In the standard theory, a charged lepton is combined with a neutrino to form a doublet. Such a doublet together with a corresponding quark doublet forms a generation. Three generations are known so far and it is of importance to know how many generations exist. In past experiments, searches for new generations have been performed by a count of the number of neutrino species, hunting new quarks, and so on. Searches for new charged heavy leptons have also been carried out, for example, by use of the DESY and SLAC e^+e^- colliding beams PETRA and PEP.[1] The obtained limit of the heavy-lepton mass was 22.7 GeV/c^2. A much higher limit of 41 GeV/c^2 was reported by UA1 at the CERN $p\bar{p}$ collider,[2] though the detection method was rather complicated compared with the case for the e^+e^- annihilation.

We have searched for sequential heavy leptons in the VENUS detector at the KEK e^+e^- colliding-beam accelerator TRISTAN. The data reported here were taken at the center-of-mass energy of 52 GeV. The central part of the detector, covering the angular range of $|\cos\theta| < 0.80$, consists of an inner chamber, a central drift chamber (CDC), and time-of-flight counters which are located inside of a superconducting solenoidal magnet of 7.5 kG. The CDC with 7104 drift cells is 300 cm in length and its inner and outer radii are 25 and 126 cm, respectively. It consists of twenty layers of axial wires parallel to the beam axis and nine layers of wires slanted from the axial wires at an angle of $\pm 3.5°$. The momentum resolution for charged particles is $\Delta p_t / p_t = p_t \times 1.5\%$, where p_t is in GeV/c. Outside the magnet are streamer tubes and a lead-glass calorimeter (barrel calorimeter). The energy resolution for electromagnetic showers is $\Delta E/E = 5\%$ for 26-GeV electrons. The details of the detector are described elsewhere.[3] The luminosity was measured with Bhabha scatterings by the barrel calorimeter as well as by the small-angle luminosity monitors. The total integrated luminosity thus obtained was 2.9 pb^{-1}.

The heavy leptons were assumed to be produced in pairs by e^+e^- annihilation and to decay into a massless neutrino and a weak doublet through the standard weak interaction. The production cross section of the heavy leptons is

$$\sigma_{L^+L^-} = \sigma_{\mu^+\mu^-}\beta(3-\beta^2)/2,$$

where β is the velocity of the heavy leptons produced. The expected event rate is less than $\frac{1}{10}$ of the multihadron events for the mass of 25 GeV/c^2 at $\sqrt{s} = 52$ GeV. The decay branching ratio of each heavy lepton used in the present analysis was 30% to the leptonic doublets and 70% to the quark doublets.[4] Thus, for about 50% of the L^+L^- productions, both of the leptons decay into hadronic jets and we searched for only the hadronic decay modes in the present analysis.

An event trigger was made by our taking a logical OR of the following:

(1) Total-energy trigger: A total energy deposited in the barrel calorimeter was greater than 5 GeV.

(2) Segment-energy-sum trigger: At least one calorimeter segment with energy greater than 0.7 GeV and two tracks with transverse momentum larger than 0.7 GeV/c were required. The barrel calorimeter is divided into 58 segments. Each segment consists of about ninety lead-glass counters.

(3) Coplanar trigger: At least two tracks which went back to back within an allowance of 10° in a projected r-ϕ plane were required. A transverse momentum larger than 0.7 GeV/c was also required for each track.

From the collected data, we first selected events with at least five good tracks and a total energy deposited in the calorimeter greater than 3 GeV. Good tracks satisfied the following conditions: (a) The number of CDC hits in the r-ϕ plane is at least 8. (b) The number of CDC hits in the r-z plane is at least 4. (c) The transverse momentum is larger than 0.2 GeV/c. (d) The minimum distance to the beam axis is less than 2 cm. (e) The z coordinate of the closest point to the beam axis is less than 20 cm. The above requirements removed most of the $\tau^+\tau^-$ events and events from beam-gas and beam-pipe interactions. After the selection there remained 673 events.

The signature of the heavy leptons is acoplanar two jets with missing energy carried away by neutrinos. In Fig. 1 are shown scatter plots of $E_{\text{vis}}/E_{\text{c.m.}}$ vs $|\cos\theta^{\text{th}}|$ (a) of the selected 673 events and of Monte Carlo data (b) for the heavy-lepton production and (c) the multihadron events. The visible energy E_{vis} is defined by $\sum E^i_{\text{LG}} + \sum P^j_{\text{trk}}$, where E^i_{LG} is the energy of the ith cluster in the lead-glass calorimeter and P^j_{trk} is the momentum of the jth track. Guided by the Monte Carlo simulation, the following selection criteria were applied in order to enhance the heavy-lepton signals against various backgrounds. (1) The ratio $E_{\text{vis}}/E_{\text{c.m.}}$ was between 0.3 and 0.8. (2) The angle between the beam axis and the thrust axis, θ^{th}, was in the region of $|\cos\theta^{\text{th}}| < 0.7$. These cuts effectively reduced the backgrounds originating from two-photon interactions and multihadron

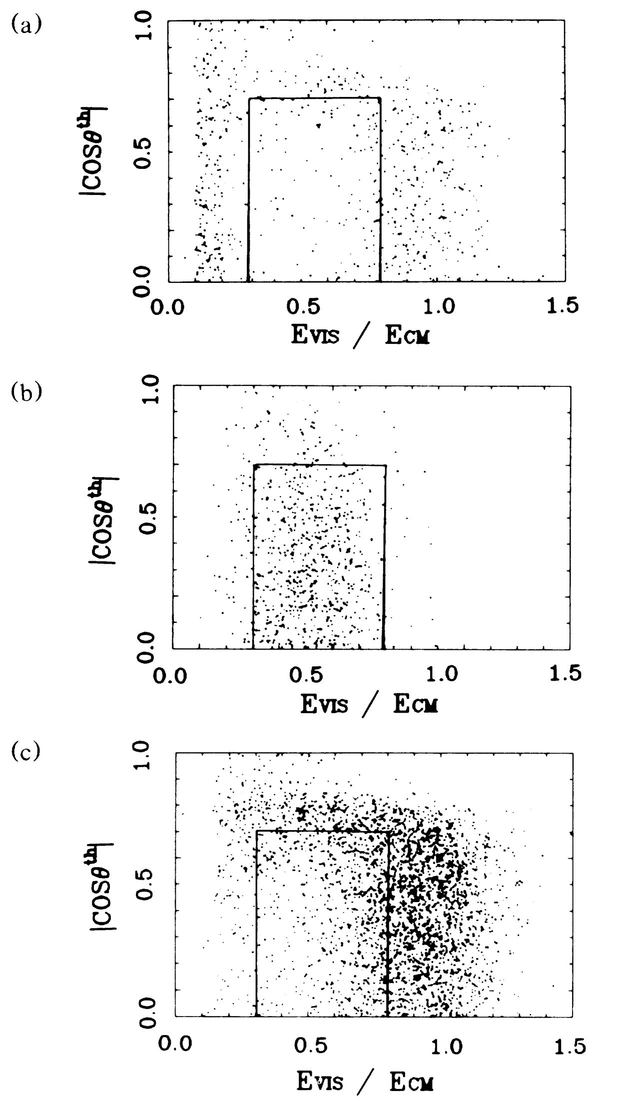

FIG. 1. Scatter plot of $E_{\mathrm{vis}}/E_{\mathrm{c.m.}}$ vs $|\cos\theta^{\mathrm{th}}|$, cosine of thrust angle θ^{th}, (a) of the selected 673 events and of the Monte Carlo events (b) for the heavy-lepton production with a mass of 25 GeV/c^2 and (c) for the multihadron production. Cuts were applied as indicated by the solid rectangles. The generated numbers of Monte Carlo events were 1000 and 4000 for (b) and (c), respectively.

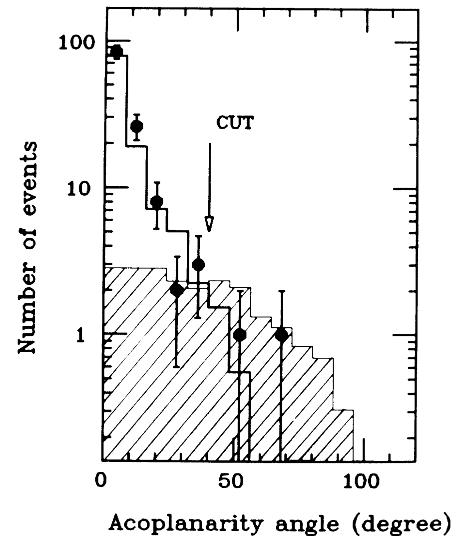

FIG. 2. A plot of the acoplanarity angle distribution. Final samples of 125 events are represented by the dots. The solid line shows the results of the Monte Carlo calculation for the multihadron events. Simulated heavy-lepton events with a mass of 25 GeV/c^2 are indicated by the hatched area. Simulated events were normalized to the integrated luminosity of 2.9 pb^{-1}.

events.

The above two cuts yielded 125 events for which an acoplanarity angle distribution was made. The acoplanarity angle was defined by

$$\cos\theta_{\mathrm{acop}} = -(\mathbf{n}_1\times\mathbf{z})\cdot(\mathbf{n}_2\times\mathbf{z})/(|\mathbf{n}_1\times\mathbf{z}|\,|\mathbf{n}_2\times\mathbf{z}|),$$

where $\mathbf{n}_1$ and $\mathbf{n}_2$ were the unit vectors pointing to the direction of the momentum sum of charged tracks and energy clusters in the calorimeter in the two hemispheres which were separated by the plane perpendicular to the thrust axis. The unit vector $\mathbf{z}$ is parallel to the direction of the electron beam. In Fig. 2 is shown the acoplanarity-angle distribution for the 125 events. The solid line shows the Monte Carlo calculation for the multihadron events. The hatched area represents an expected yield from a heavy lepton with a mass of 25 GeV/c^2. Events above 40° in acoplanarity angle were treated as possible candidates. The acceptance of heavy leptons surviving the event selections was estimated by the Monte Carlo simulation to be 22% and nearly constant for the mass range between 20 and 26 GeV/c^2. Inefficiency due to the hardware trigger was found to be negligible. The expected number of heavy leptons with the mass of 25 GeV/c^2 was 7.4 ± 1.3 events, while 2.0 ± 0.6 events were expected from the multihadron events, where the errors include the uncertainties in the Monte Carlo simulations as described below. We observed two candidates, consistent with those from the background of the multihadron events. There is no evidence for heavy-lepton production.

In those Monte Carlo calculations, LUND 5.3[5] was used for the fragmentation of the quarks. Radiative corrections up to order α^3 according to Berends, Kleiss, and Jadach[6] and the effect of Z^0 were taken into account. Generated events were processed through a detector simulator and then exactly the same program as that for real events was used to select the simulated events.

The systematic uncertainties of the acceptance were estimated by the change of the parameters in the simula-

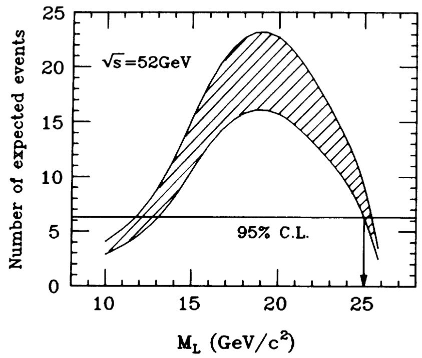

FIG. 3. Expected numbers of heavy-lepton events as a function of mass at $\sqrt{s}=52$ GeV (the hatched band indicates systematic errors). The upper bound of the number of events with 95% confidence level in the present experiment is indicated by the solid line.

tion and the cuts. They were due to the fragmentation model[7] ($\simeq 10\%$), the cuts for the selection ($\simeq 5\%$), the radiative correction ($\simeq 3\%$), the decay branching ratio ($\simeq 10\%$), the statistics in the Monte Carlo simulation ($\simeq 5\%$), and the luminosity measurements ($\simeq 5\%$). The total systematic error was 17% if these uncertainties were combined in quadrature.

With use of the efficiency and the integrated luminosity, a limit on the mass of the sequential heavy lepton was obtained. The expected number of events for its production at $\sqrt{s}=52$ GeV is calculated as a function of the heavy-lepton mass and shown in Fig. 3 as a hatched band, the width of which represents the systematic errors. The 95%-confidence-level (C.L.) upper limits corresponding to the observed two events is also shown in the figure. The mass limit thus obtained is 25.0 GeV/c^2. This lower bound is, however, a conservative estimate, since we did not subtract the expected background of 2.0 ± 0.6. If we subtract this background, the lower mass limit of 25.4 GeV/c^2 at 95% confidence level was obtained.

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[7]The fragmentation model in LUND 5.3 is characterized by the functions

$$F(Z)=[(1-Z)^A/Z]\exp(-BM_t^2/Z),$$

$$f(p_t)=(1/\pi\sigma^2)\exp(-p_t^2/\sigma^2),$$

where $M_t^2=m^2+p_t^2$ and $Z=(E'+p')/(E_q+p_q)$. E' and p' stand for the energy and momentum of fragmented hadrons and E_q and p_q for those of the original partons. The values used in our Monte Carlo simulation are $A=1.0$, $B=0.63$, $\sigma=0.37$, and $Y_{\min}=0.02$, which is a minimum scaled invariant mass squared. These values were changed by the following amounts to see the systematic effect due to the fragmentation model: $0.5 \le A \le 1.5$, $0.2 \le B \le 1.0$, $0.2 \le \sigma \le 0.6$, and $0.01 \le Y_{\min} \le 0.03$. A different fragmentation model (LUND 6.3, parton-shower model) was also used to calculate the acceptance. The result obtained was consistent with that from LUND 5.3 within statistical errors.