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Rapid Communications

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Search for sequential heavy leptons in e^+e^- collisions at $\sqrt{s}=52$ GeV

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We have searched for new sequential heavy leptons $L^\pm$ in e^+e^- collisions at $\sqrt{s}=52$ GeV using the TOPAZ detector at the KEK storage ring TRISTAN. In the collected data with an integrated luminosity of 3.6 pb^{-1}, no evidence for $L^\pm$ production has been observed. A lower mass limit for $L^\pm$ is determined to be 25.5 GeV/c^2 at 95% confidence level.

As in the case of the τ-lepton discovery, new sequential heavy leptons $L^\pm$ will be the key to disclose a possible new (fourth) generation of quarks and leptons. Many groups have searched for these particles at e^+e^- and $p\bar{p}$ colliders, but no positive evidence has been found. The lower-mass limit obtained at the DESY e^+e^- collider PETRA is 22.7 GeV/c^2 [95% confidence level (C.L.)][1] and that at the CERN $p\bar{p}$ collider is 41 GeV/c^2 (90% C.L.).[2]

In this Rapid Communication we report the result of a sequential-heavy-lepton search in e^+e^- interactions with the TOPAZ detector at the KEK storage ring TRISTAN. The study is based on data collected at $\sqrt{s}=52$ GeV with an integrated luminosity of 3.6 pb^{-1}.

The general features of the TOPAZ detector are described elsewhere.[3] The characteristics of the detector elements crucial to this analysis are as follows: The time-projection chamber (TPC), located in the solenoidal magnetic field of 1.0 T, covers 90% of the solid angle and analyzes charged-particle momenta with a momentum resolution in % of $\sigma_{p_t}/p_t=[(1.5p_t)^2+(1.6)^2]^{1/2}$, where p_t is given in GeV/c. The barrel calorimeter (BCL) is an array of 4300 lead-glass counters of $20X_0$ (X_0 is radiation length) which covers polar angles from 32° to 148°, with an energy resolution in % of $\sigma_E/E=[(8.0/\sqrt{E})^2+4.2^2]^{1/2}$, where E is in GeV. The polar-angle regions of $12°<\theta<32°$ and $148°<\theta<168°$ are covered by the end-cap calorimeters (ECL) of the lead-PWC (proportional wire chamber) sandwich type ($18X_0$), whose energy resolution is 6.7% for 26-GeV electrons. In addition to these elements, the inner drift chamber (IDC) and the time-of-flight counters (TOF) are used for event triggering.

In the TOPAZ data-acquisition system, trigger signals were generated for events which satisfied one of the following conditions:[4] (1) the total-energy trigger: the energy deposit > 4 GeV in the BCL, or > 10 GeV in one of the ECL's; (2) the partial-energy trigger: > 1 GeV in any two of the BCL segments (the BCL is divided into 3 segments along the z axis), or > 3 GeV in any of the segments of both ECL's (each ECL is segmented into the inner and outer rings), or > 1 GeV in one of the BCL segments and > 3 GeV in one of the ECL segments; and (3) the track trigger: the number of tracks ≥ 2 in both IDC and TOF with their opening angle > 45° (pretrigger), and at least one forward and one backward track originating from the beam crossing point are observed in the TPC.

In this study we searched for sequential heavy leptons through the process

$$e^+ + e^- \rightarrow L^+ + L^- ,$$

where $L^\pm$ decay via the standard weak interaction

$$L^\pm \rightarrow \text{"}W\text{"} + \nu_L$$
$$\hookrightarrow (ud),\ (cs),\ e\nu_e,\ \mu\nu_\mu,\ \text{or}\ \tau\nu_\tau .$$

We focused our study on the hadronic decay modes, since the branching ratio for the hadronic decays is relatively large (67%), when the masses of quarks and leptons are neglected in the phase-space calculation. We required at least one $L^\pm$ to decay into hadrons. The identification of this mode from the background is relatively easy. The neutrinos escape the detector and carry away a large fraction of the $L^\pm$ energy and the quark-antiquark pair emerge as a hadron jet. Therefore, the strategy to search for $L^\pm$ is to look for an acoplanar event with large missing energy. A typical event shape is schematically shown in Fig. 1.

Monte Carlo simulations were carried out for determining the event-selection criteria and for calculating the detection efficiency. The L^+L^- events were generated according to the standard cross-section formula for fermion-pair production:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\beta_L[1+\cos^2\theta+(1-\beta_L^2)\sin^2\theta] ,$$

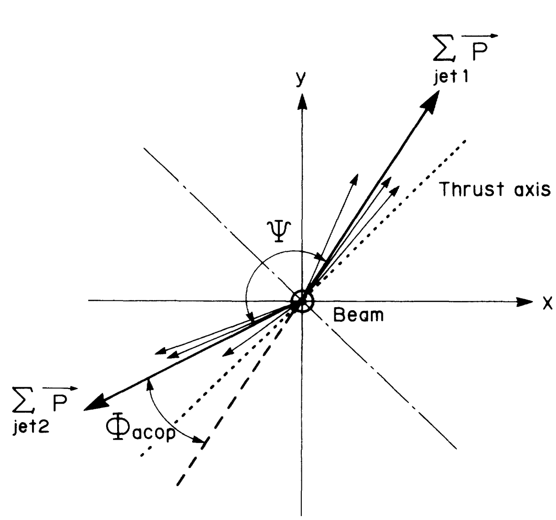

FIG. 1. A schematic view of a typical heavy-lepton event in a plane perpendicular to the beam direction.

where θ is the polar angle and β_L is the $L^\pm$ velocity in the c.m. system. The initial-state radiation was taken into account in the calculation according to Berends and Kleiss.[5] In the decay of $L^\pm$, the mass of the neutrino was assumed to be zero. Hadronization of quarks was simulated by using program packages in the Monte Carlo program EPOCS.[6]

In order to study the possible background, hadronic events were simulated by the Monte Carlo program LUND 6.3 (Ref. 7) with five quark flavors.[8] Two-photon events, τ-pair events, and Bhabha events were also simulated.

Based on these simulations, we set the selection criteria for the L^+L^- events as follows.

(1) At least 5 tracks originating from the interaction point have transverse momenta greater than 0.15 GeV/c.

(2) One of the hadron jets has a mass larger than 4 GeV/c^2.

(3) The total energy deposit in the calorimeters exceeds 3 GeV.

(4) The longitudinal-momentum imbalance $|\sum p_z|/\sum|p|$ is less than 0.5.

(5) The number of energy clusters with energies greater than half the beam energy is at most one.

(6) The cosine of the polar angle of the thrust axis, $\cos(\theta_{th})$, is less than 0.7.

Criteria (1) and (2) reduced the background from τ-pair production. Criteria (3) and (4) suppressed the two-photon background. Criterion (5) rejected the background from Bhabha events. Criterion (6) was to assure that almost all of the final-state particles were detected in the sensitive area of the detector. The detection efficiency for L^+L^- production was estimated to be 70% under the above conditions.

After these cuts, 557 events survived, which included hadronic events. The visible-energy (E_{vis}) distribution of these events is shown in Fig. 2 together with the results of the Monte Carlo simulations, where the visible energy

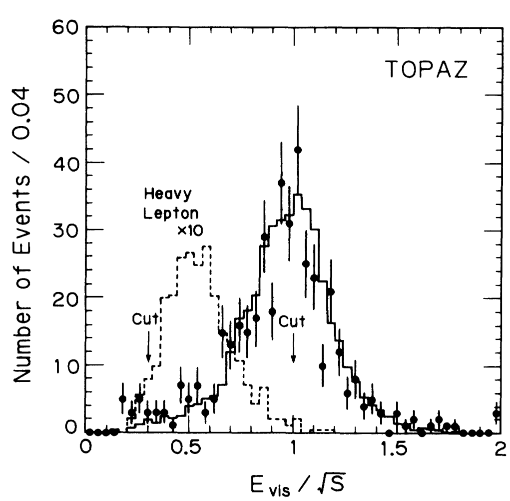

FIG. 2. The visible-energy distribution after cuts (1)–(6). The solid and dashed histograms show the Monte Carlo results for hadronic events and for heavy-lepton events with $M_L = 25$ GeV/c^2, respectively. The number of heavy-lepton events is magnified by a factor of 10.

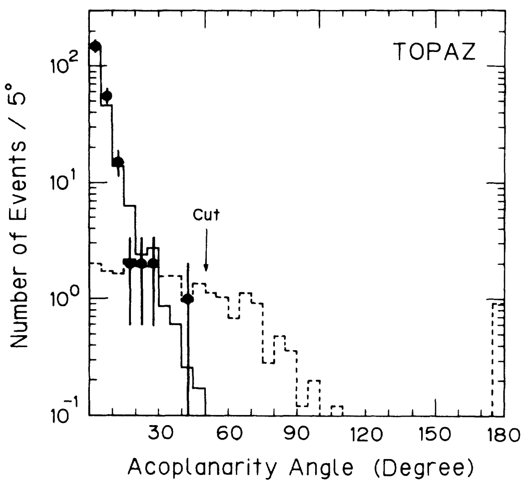

FIG. 3. The acoplanarity-angle distribution after the visible energy cut. The solid and dashed histograms show the Monte Carlo results for hadronic events and for heavy-lepton events with $M_L = 25$ GeV/c^2, respectively.

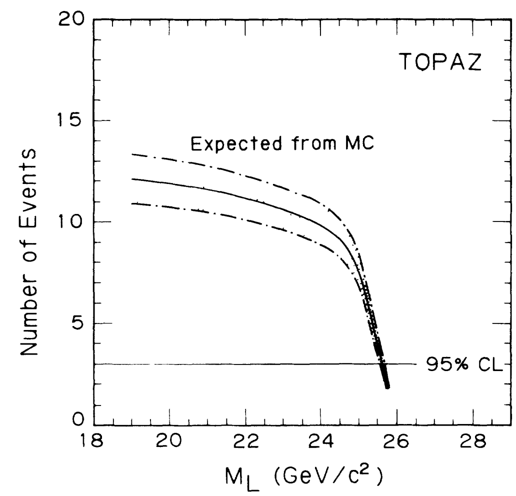

FIG. 4. The expected number of heavy-lepton events as a function of M_L. The uncertainties in the Monte Carlo simulation are shown by the dotted area.

means the sum of the energies measured by the calorimeters and those determined by the TPC tracks assuming all final-state charged particles to be pions. The solid histogram shows the Monte Carlo result for hadronic events. The dashed histogram shows the expected distribution for L^+L^- events, where the mass of $L^\pm$ is assumed to be 25 GeV/c^2. The number of the generated hadronic events is normalized by the integrated luminosity and the number of the L^+L^- events in the figure corresponds to ten times the actual luminosity. For the hadronic events, this distribution peaks at the total c.m. energy, whereas the L^+L^- events are distributed around about half the total c.m. energy. The experimental results are well reproduced by the Monte Carlo simulation of hadronic events.

To further select L^+L^- candidates, we required $0.3 < E_{vis}/\sqrt{s} < 1.0$. The lower energy cut is to reduce the two-photon background and the higher energy cut is to suppress hadronic events. After these cuts, a total of 226 events were left. The Monte Carlo simulation for the hadronic process (LUND 6.3) predicts 224.6 events, clearly consistent with the observation.

The acoplanarity-angle distribution of the remaining events is shown in Fig. 3. The acoplanarity angle is defined as

$$\Phi_{acop} = 180° - \Psi ,$$

where Ψ is the angle between two planes defined by the beam direction and directions of momentum sums in the two hemispheres divided by a plane perpendicular to the thrust axis (Fig. 1). If there are neither tracks nor energy clusters in one of the hemispheres, the acoplanarity angle is defined to be 180°. The results of the simulations are shown by the solid and dashed histograms for the hadronic and L^+L^- events, respectively. The distribution shows a sharp decrease for the hadronic events, while the acoplanarity angles of L^+L^- events are distributed rather widely. The obtained data agree well with the expectation for the hadronic events.

Requiring an acoplanarity angle larger than 50°, we have no event left in the real data, whereas 7.5 events are expected if a new sequential heavy lepton with a mass of 25 GeV/c^2 exists. The expected background is less than 2%, which arises from hadronic events (1.2%), τ-pair production (0.5%), two-photon processes (0.1%), and the Bhabha process (< 0.1%).

In Fig. 4, the expected number of L^+L^- events after the cuts mentioned above is shown by the solid line as a function of the $L^\pm$ mass at $\sqrt{s} = 52$ GeV.[9] The uncertainties in the Monte Carlo simulation were estimated by varying the fragmentation parameters within the allowed region. The results are shown by the dotted area in the figure. The effect on the mass limit is less than 0.1 GeV/c^2. Since we have no observed events, the mass region where the expected number of events is larger than 3.0 is excluded at the 95% confidence level. Thus we obtained the lower mass limit for the sequential heavy lepton to be 25.5 GeV/c^2 (95% C.L.). The effect of the value of the cut on the acoplanarity-angle distribution was also examined. When we change the value to 40°, for example, the lower-mass limit decreases by only 0.05 GeV/c^2.

In conclusion, we have searched for sequential heavy leptons in e^+e^- collisions at $\sqrt{s} = 52$ GeV, and found no candidate event. The lower-mass limit is set at 25.5 GeV/c^2 at 95% C.L.

We are grateful to the KEK directorate for bringing TRISTAN into operation on schedule. We thank the accelerator physicists and engineers for the successful operation of TRISTAN, and the cryogenic group for their maintenance of the TOPAZ magnet cooling system. One of us (R.E.) wishes to thank the Inoue Foundation for Science for partial support. Finally, we thank all engineers and technicians at KEK and collaboration institutes: H. Inoue, N. Kimura, K. Kono, H. Masuda, K. Norimura, K. Shiino, M. Tanaka, K. Tsukada, N. Ujiie, and H. Yamaoka.

[1]For example, see S. Komamiya, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, 1985,* edited by M. Konuma and K. Takahashi (Research Institute for Fundamental Physics, Kyoto University, Kyoto, 1986), p. 612.

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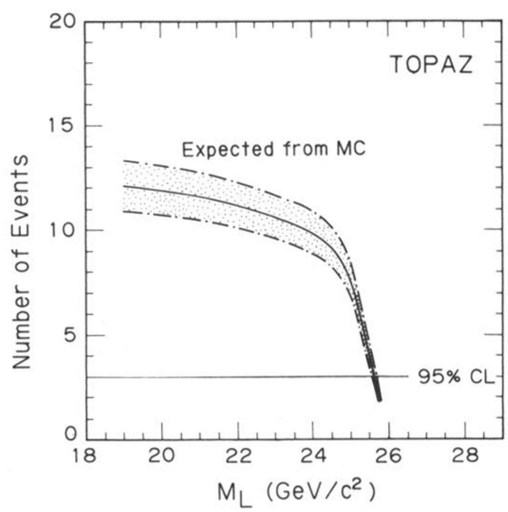
[8]Hadronic events were simulated also by the Monte Carlo program EPOCS. The result agreed well with that of LUND 6.3.

[9]We only looked for $M_L > 20$ GeV/c^2, because lower masses are covered by previous experiments (Ref. 1).



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