Search for the Production of the Final States $\tau^+\tau^-e^+e^-$, $\tau^+\tau^-\mu^+\mu^-$, and $\tau^+\tau^-\pi^+\pi^-$ in e^+e^- Collisions at $\sqrt{s}=29$ GeV

T. Barklow,[2] W. R. Innes,[2] M. Petradza,[2] A. Snyder,[2] D. P. Stoker,[2] S. R. Wagner,[2] G. S. Abrams,[1] D. Amidei,[2] A. R. Baden,[1] A. M. Boyarski,[2] J. Boyer,[1] P. R. Burchat,[2] D. L. Burke,[2] F. Butler,[1] J. M. Dorfan,[2] G. J. Feldman,[2] G. Gidal,[1] L. Gladney,[2] M. S. Gold,[1] G. Goldhaber,[1] L. J. Golding,[1] J. Haggerty,[1] G. Hanson,[2] K. Hayes,[2] D. Herrup,[1] R. J. Hollebeek,[2] J. A. Jaros,[2] I. Juricic,[1] J. A. Kadyk,[1] D. Karlen,[2] A. J. Lankford,[2] R. R. Larsen,[2] B. W. LeClaire,[2] M. E. Levi,[3] N. S. Lockyer,[2] V. Lüth,[2] M. E. Nelson,[1] R. A. Ong,[2] M. L. Perl,[2] B. Richter,[2] K. Riles,[2] P. C. Rowson,[1] T. Schaad,[3] H. Schellman,[1] W. B. Schmidke,[1] P. D. Sheldon,[1] G. H. Trilling,[1] D. R. Wood,[1] and J. M. Yelton[2]

[1]*Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720*
[2]*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[3]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138*
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We have searched for the reaction $e^+e^- \to \tau^+\tau^-f\bar{f}$, where f is either an electron, muon, or charged pion, at $\sqrt{s}=29$ GeV using the Mark II detector at the SLAC storage ring PEP. One candidate event is found while 2.3 events are expected from known processes. We would expect to see 11 events if the cross section for $e^+e^- \to \tau^+\tau^-f\bar{f}$ at $\sqrt{s}=29$ GeV were enhanced by the factor of 4.7 which the ALEPH Collaboration reports for $\sqrt{s}=91$ GeV. We also look for $e^+e^- \to e^+e^-f\bar{f}$ and $e^+e^- \to \mu^+\mu^-f\bar{f}$, and for $e^+e^- \to \tau^+\tau^-\gamma$, using a similar analysis procedure, and see the number of events predicted by the standard model.

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The ALEPH Collaboration has recently reported an anomalously large number of events of the type

$$e^+e^- \to \tau^+\tau^-f\bar{f}, \quad f=e^-,\mu^-,\pi^+,$$

at $\sqrt{s}=91$ GeV [1]. An excess of $\tau^+\tau^-f\bar{f}$ events is seen in comparisons both of the observed number of $\tau^+\tau^-f\bar{f}$ events with the standard model prediction for the absolute rate and of the number of $\tau^+\tau^-f\bar{f}$ events relative to $e^+e^-f\bar{f}$ and $\mu^+\mu^-f\bar{f}$ events. In this paper we report on a search for events of the type $\tau^+\tau^-f\bar{f}$ at $\sqrt{s}=29$ GeV using 205 pb^{-1} of data collected by the Mark II detector at the SLAC storage ring PEP.

Selecting four lepton candidates.— The Mark II detector has been described previously [2]. The drift-chamber charged-particle tracking systems covered the central 85% of the solid angle. The lead–liquid-argon electromagnetic calorimeter covered 65% of the solid angle. We used tracks which satisfy the following requirements. Charged tracks must have a momentum in the plane perpendicular to the beam axis greater than 0.08 GeV/c. An energy cluster in the calorimeter is treated as an independent neutral track if it has an energy greater than 0.2 GeV and is not associated with a charged track by the calorimeter-cluster-reconstruction algorithm.

Candidate events must have four or six charged tracks with total charge equal to zero. The total number of tracks, charged and neutral, must be no greater than ten. We require that no pair of charged particles be consistent with photon conversion [3]. The total energy in an event, defined to be the sum of the energies of all charged and neutral tracks, must be greater than 9 and less than 27

GeV. This favors the type of events we desire (we discuss this event type in detail below). The thrust axis is calculated using all charged and neutral tracks. To ensure our ability to simulate the detector response, we require that the absolute value of the cosine of the angle between the thrust axis and the beam axis be less than 0.74.

Selecting $\tau^+\tau^-V$ candidates.— The remainder of our analysis consists of testing the hypothesis that the event was produced by the reaction $e^+e^- \to \tau^+\tau^-f\bar{f}$. We note here that the following selection procedure was tuned on a sample of $\tau^+\tau^-\mu^+\mu^-$ Monte Carlo [4] events in which all $\tau^+\tau^-$ masses were greater than 9 GeV/c^2 and all $\mu^+\mu^-$ masses were between 0.3 and 5 GeV/c^2. This is the event type for which ALEPH reported an enhanced rate. The production amplitude for these events is dominated by the Feynman diagram with the $f\bar{f}$ appearing as radiation from an outgoing τ leg.

The $\tau^+\tau^-f\bar{f}$ selection must discriminate against several physics backgrounds. The most troublesome are hadronic $\tau^+\tau^-$, $e^+e^-f\bar{f}$, and $\mu^+\mu^-f\bar{f}$ events. As we describe the selection procedure we will identify which background is being reduced.

The first step in isolating the signal is to assign the charged and neutral tracks in the event to the τ-decay products and to the f and $\bar{f}$. We try all possible such "$\tau^+\tau^-f\bar{f}$ configurations" and keep the one that is most consistent with the reaction $e^+e^- \to \tau^+\tau^-f\bar{f}$. Using the nomenclature of the ALEPH paper we call the sum of the four-momenta of the f and $\bar{f}$ tracks the "V." The V must have a charge of zero and a mass of less than 5 GeV/c^2. The angle between the f and $\bar{f}$ tracks must also

be less than 110° in the laboratory frame.

The $\tau^+\tau^-$ candidate system is the initial e^+e^- system minus the measured V, i.e., the V-missing-mass system. We require that the invariant mass of this system be at least 14 GeV/c^2.

After assigning charged tracks to the V, the remaining charged and neutral tracks are boosted to the center of mass of the $\tau^+\tau^-$ candidate system. A thrust analysis is performed on these tracks in this frame and they are then grouped according to thrust hemispheres. If after this grouping the net charge of each thrust hemisphere is not ± 1, the $\tau^+\tau^- f\bar{f}$ configuration is discarded. To eliminate $\tau^+\tau^-\gamma$ events, we discard configurations for which the mass of the charged particles in one hemisphere combined with the V is less than 1.8 GeV/c^2. We form two four-vectors p_i by summing the four-momenta of the charged and neutral tracks assigned to each thrust hemisphere i ($i = 1,2$). We define m_i to be the invariant mass of p_i.

We use the fact that p_i should correspond to the four-vector sum of all visible decay products of one of the τ leptons to impose a series of cuts on p_i. We require that the angle between p_1 and p_2 be greater than 90° in the laboratory frame. Because of our choice of signal this costs little and ensures that the events we do get have the kinematics of interest. Next we calculate the mass of the sum of the four-momenta of p_k and the V where $p_k = p_1$, if the V makes a smaller angle to p_1 than p_2 in the laboratory frame and $p_k = p_2$ otherwise. To reduce $\tau^+\tau^-$ and hadronic background, we require that this mass be greater than 3.0 GeV/c^2.

In order to further reduce hadronic background we keep only configurations for which the τ-decay product masses m_i are small enough. The maximum allowed value depends on the number of charged and neutral tracks in thrust hemisphere i (Table I). Figure 1 shows the hemisphere mass distribution for the five cases.

We also cut on the variables $\eta_i \equiv E_i/E_\tau$, $i = 1,2$, where E_i is the energy of p_i and E_τ is half the center-of-mass energy of the $\tau^+\tau^-$ candidate system. As defined, η_i is the fraction of the τ's energy that goes into visible decay products. The primary purpose of cutting on this variable is to remove background from $e^+e^- \to e^+e^- f\bar{f}$, $\mu^+\mu^- f\bar{f}$. As a consequence, the cut on η_i will be harder

for leptonic τ decays than for hadronic τ decays. We distinguish between leptonic and hadronic decays according to m_i. If m_i is less than 0.15 GeV/c^2, then the decay is considered a "leptonic" decay, otherwise it is a "hadronic" decay. Note that with this scheme τ decays to single charged pions are classified as leptonic decays.

The cuts on η_i are as follows. If p_i is classified as a leptonic τ decay, then η_i must be greater than 0.16 and less than 0.77. The lower limit is imposed to reject unusual low-multiplicity hadronic events and the upper limit is imposed to reject $e^+e^- f\bar{f}$ and $\mu^+\mu^- f\bar{f}$ events. If both p_1 and p_2 are classified as leptonic τ decays, then we further require that the sum $\eta_1 + \eta_2$ be less than 1.4. If p_i is classified as a hadronic τ decay, then η_i must be greater than 0.22. Again the lower limit is imposed to reject hadronic events while there is no upper limit because the $e^+e^- f\bar{f}$ and $\mu^+\mu^- f\bar{f}$ background is negligible in this case. We call a $\tau^+\tau^- f\bar{f}$ configuration which passes all of the above cuts a "valid $\tau^+\tau^- f\bar{f}$ configuration."

At this point the hadronic Monte Carlo [5] calculations predict that there will still be a substantial background. To remove the remaining hadronic events we calculate the square of the missing mass in each τ decay and compare it with the distribution predicted by the $\tau^+\tau^- f\bar{f}$ Monte Carlo calculation. Hadronic τ decays have a missing mass squared of zero, within experimental resolution, and the spectrum for the missing mass squared of leptonic τ decays is broader with the mean shifted to a small positive value. Hadronic events tend to produce
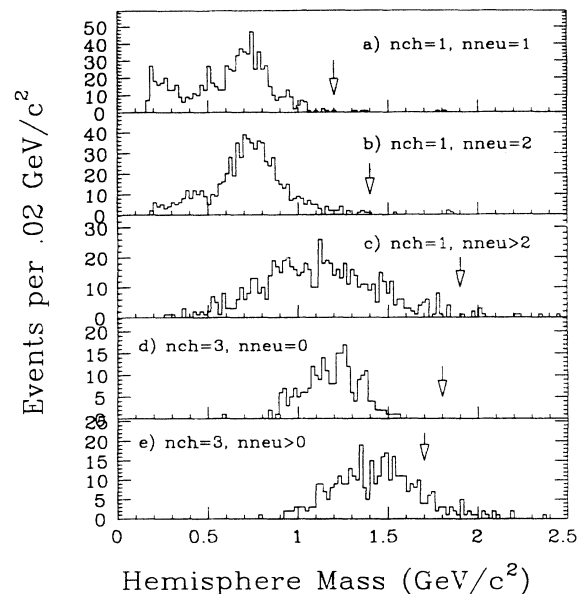

FIG. 1. Hemisphere mass distribution from the $\tau^+\tau^-\mu^+\mu^-$ simulation for (a) 1 charged track, 1 neutral track; (b) 1 charged track, 2 neutral tracks; (c) 1 charged track, ≥ 3 neutral tracks; (d) 3 charged tracks, no neutral tracks; and (e) 3 charged tracks, ≥ 1 neutral track. The arrows indicate the locations of the cuts.
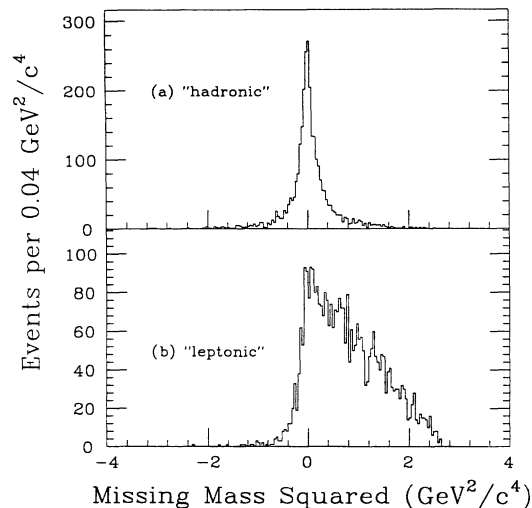
TABLE I. Hemisphere mass cut.

Number of charged tracks in hemisphere	Number of neutral tracks in hemisphere	Maximum acceptable hemisphere mass (GeV/c^2)
1	≤ 1	1.2
1	2	1.4
1	≥ 3	1.9
3	0	1.8
3	≥ 1	1.7

FIG. 2. Missing-mass-squared distributions from the Monte Carlo simulation of (a) "hadronic" τ decays, and (b) "leptonic" τ decays.
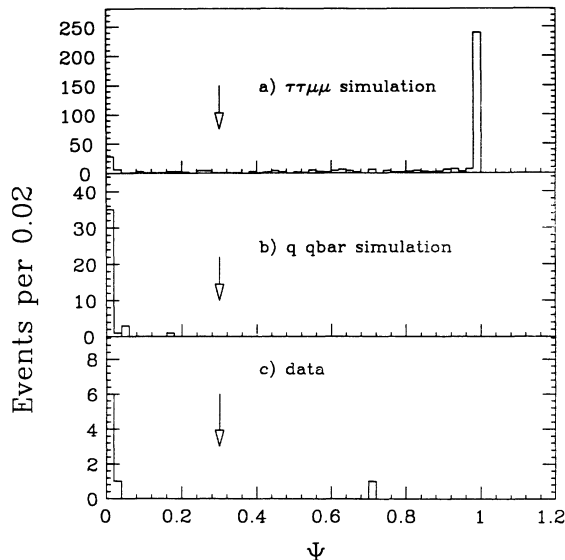

FIG. 3. The distribution of Ψ for (a) the $\tau^+\tau^-\mu^+\mu^-$ simulation, (b) the $q\bar{q}$ simulation, and (c) the data. The arrows show the location of the cut.

large negative values for the missing mass squared because the assumption that tracks come from the decay of a τ is wrong.

Let M_{v1} and M_{v2} be the missing masses for the τ decays in thrust hemispheres 1 and 2, respectively. Let θ and ϕ be the polar and azimuthal angles of the τ lepton in hemisphere 1 in the $\tau^+\tau^-$ candidate rest system. Figure 2 contains the distributions in M_{vi}^2 for $e^+e^- \to \tau^+\tau^-\mu^+\mu^-$ Monte Carlo events. A full detector simulation has been used in calculating M_{vi}^2 in Fig. 2 with the exception that θ and ϕ are taken directly from the Monte Carlo generator. Figure 2(a) shows the distribution of M_{vi}^2 for hadronic τ decays and Fig. 2(b) shows the distribution for leptonic decays.

Let $f_H(M_{vi}^2)$ be the distribution in M_{vi}^2 for hadronic τ decays, and $f_L(M_{vi}^2)$ be the distribution in M_{vi}^2 for leptonic τ decays. They are normalized such that their peak values are 1.0. Since we cannot measure θ and ϕ, we allow them to vary. Let

$$\psi \equiv \max_{\substack{0 \le \theta \le \pi \\ 0 \le \phi \le 2\pi}} f_1(M_{v1}^2(\theta,\phi)) f_2(M_{v2}^2(\theta,\phi)) ,$$

where $f_i(x) = f_L(x)$ if thrust hemisphere i is classified as a leptonic τ decay and $f_i(x) = f_H(x)$ if thrust hemisphere i is classified as a hadronic τ decay.

We define Ψ to be the maximum value of ψ over all valid $\tau^+\tau^-f\bar{f}$ configurations in an event. Figure 3(a) shows the distribution of Ψ from the $\tau^+\tau^-\mu^+\mu^-$ simulation, which we can compare to the distribution from the $q\bar{q}$ simulation shown in Fig. 3(b). We see that Ψ clearly separates $\tau^+\tau^-\mu^+\mu^-$ events from hadronic events. For our final cut we require that Ψ be greater than 0.3. Figure 3(c) shows the distribution of Ψ from the data. Our

lone $\tau^+\tau^-f\bar{f}$ candidate has $\Psi = 0.71$ and is shown in Fig. 4.

Table II contains the expected number of events with $\Psi > 0.3$ for various processes. Summed over $\tau^+\tau^-e^+e^-$, $\tau^+\tau^-\mu^+\mu^-$, and $\tau^+\tau^-\pi^+\pi^-$, the total number of events expected for $e^+e^- \to \tau^+\tau^-f\bar{f}$ is 2.33.

Systematics. — To check our efficiency and cross-section calculations for $e^+e^- \to \tau^+\tau^-f\bar{f}$, we modify
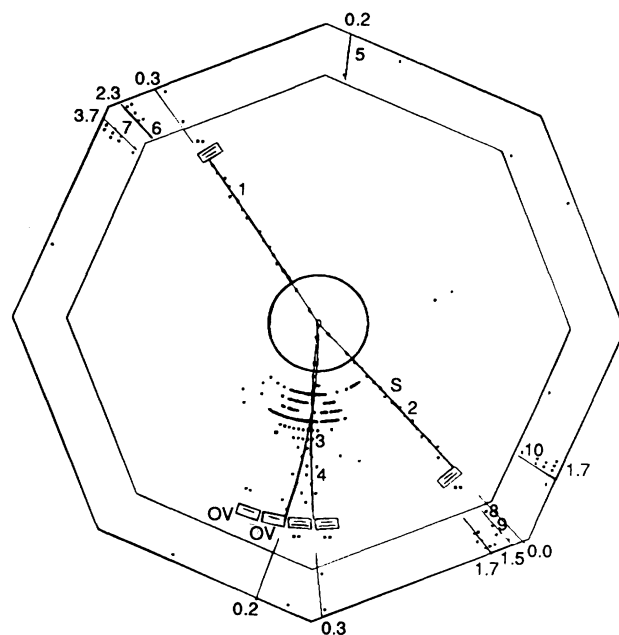

FIG. 4. Lone $\tau^+\tau^-V$ candidate event viewed along the beam axis.

TABLE II. Expected events from known processes. Items within parentheses are not included in the total.

Process	Number of events expected to pass $\tau^+\tau^-f\bar{f}$ selection
$e^+e^- \rightarrow \tau^+\tau^-e^+e^-$	1.28 ± 0.10
$e^+e^- \rightarrow \tau^+\tau^-\mu^+\mu^-$	0.69 ± 0.04
$e^+e^- \rightarrow \tau^+\tau^-q\bar{q}$	0.36 ± 0.04
$e^+e^- \rightarrow q\bar{q}$	(<1.0)
$e^+e^- \rightarrow \tau^+\tau^-$	(0.4 ± 0.4)
$e^+e^- \rightarrow \mu^+\mu^-u\bar{u}$	(0.015)
Total	2.33 ± 0.11

parts of our analysis in order to make it efficient for similar processes with larger cross sections. For example, if we keep events with identified photon conversions, we expect 0.9 additional signal event and 2.0 $\tau^+\tau^-\gamma$ events. In the data we find 2.0 new events. The totals without the pair conversion cuts are 5.3 expected, 3 observed.

To get better statistics, we can look for $\tau^+\tau^-\gamma$ events in which the photon does not convert inside our tracking chambers. By defining our V to be a calorimeter photon with energy greater than 0.6 GeV and otherwise leaving the analysis unchanged we can check our $\tau^+\tau^-$ acceptance and efficiency. Using the Monte Carlo generator KORALZ3 [6] we estimate that there should be 155 ± 8 $\tau^+\tau^-\gamma$ events with $\Psi > 0.3$ in the data. We find 154. Furthermore, the breakdown of the number of events by τ-decay type follows expectations.

We next modify our analysis so that it selects $e^+e^-f\bar{f}$ and $\mu^+\mu^-f\bar{f}$ final states. This will check our acceptance and efficiency for finding the V. Recall that we used the variable η_i to remove $e^+e^-f\bar{f}$ and $\mu^+\mu^-f\bar{f}$ events. To select $e^+e^-f\bar{f}$ and $\mu^+\mu^-f\bar{f}$ events we require that both thrust hemispheres be classified as leptonic decays, that $\eta_i > 0.78$, $i = 1,2$, and that $\eta_1 + \eta_2 > 1.64$. Aside from these modifications our analysis for $e^+e^- \rightarrow e^+e^-f\bar{f}$, $\mu^+\mu^-f\bar{f}$ is identical to the one for $e^+e^- \rightarrow \tau^+\tau^-f\bar{f}$.

There are 65 data events which pass our cuts for $e^+e^- \rightarrow e^+e^-f\bar{f}$, $\mu^+\mu^-f\bar{f}$, compared to 62.2 events expected from all processes.

In summary, we see one candidate event for the final state $\tau^+\tau^-f\bar{f}$ in e^+e^- collisions at $\sqrt{s} = 29$ GeV. We expect to see 2.33 such events due to known processes. We set an upper limit on a uniform enhancement factor of 2.0 at the 95% confidence level. If the production of $\tau^+\tau^-f\bar{f}$ were enhanced by the factor of 4.7 which ALEPH reports at $\sqrt{s} = 91$ GeV, then we would expect to see 11.0 events. The probability of seeing 0 or 1 event when expecting 11.0 is 2×10^{-4}.

[1] ALEPH Collaboration, D. Decamp et al., Phys. Lett. B 263, 112 (1991). ALEPH reports seeing 15 events where they expect 3.2.

[2] R. H. Schindler et al., Phys. Rev. D 24, 78 (1981).

[3] The conversion test is based on the opening angle, separation, and distance from the origin, all at the location of closest approach. See M. E. Nelson, Ph.D. thesis, LBL Report No. LBL-16724, 1983.

[4] This sample, and all other four-lepton final-state samples used in this paper, was generated with the Monte Carlo program written by Berends, Daverveldt, and Kleiss which is described in F. A. Berends et al., Nucl. Phys. B253, 441 (1985).

[5] This number, and others from the hadronic Monte Carlo program, is sensitive to the details of the generator. We use JETSET 6.3. See A. Petersen, Phys. Rev. D 37, 1 (1988), for a complete description. This Monte Carlo program is used only for tuning cuts. It is not used in obtaining the result in any other way.

[6] We use the Monte Carlo program KORALZ3 [S. Jadach and B. F. L Ward, CERN Report No. TH-5994-91, 1991 (to be published)] to simulate $\tau^+\tau^-$ and $\tau^+\tau^-\gamma$ production.