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Charged Particle Pair Production Associated with a Lepton Pair in Z Decays: Indication of an Excess in the Tau Channel

The ALEPH Collaboration*

Abstract

In a sample of 200,000 Z decays, events with two leptons and an additional pair of charged particles are studied. The 35 events found show a possible excess in the tau channel compared with the expectation from electroweak processes. The features of the events are consistent with radiation of virtual photons.

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SECTION 1 - Introduction

We report here a study of a simple configuration with two leptons and an additional pair of charged particles produced in the process

$$Z \rightarrow \ell^+ \ell^- V \quad (1)$$

where ℓ is a lepton, i.e. e , μ , or τ , and "V" is a charged particle-antiparticle pair, i.e. $V = e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-$, originating at the interaction point.

All the data collected by the ALEPH detector in 1989 and 1990 are used, and consist of 2×10^5 observed Zs, corresponding to an integrated luminosity of 8.5 pb^{-1} . The ALEPH detector is described elsewhere [1]. The components that play essential roles in this analysis are: the inner tracking chamber (ITC), time projection chamber (TPC), luminosity calorimeter (LCAL), electromagnetic calorimeter (ECAL), hadronic calorimeter (HCAL) and the muon chambers. For the present purpose, the most important characteristics of the detector are the efficiency and precision for the reconstruction of charged particle momenta as well as the completeness of the solid angle coverage of the calorimetry. In addition, the above elements of the detector, when used together, provide efficient high-purity identification of electrons, muons, and pions.

SECTION 2 - $\ell^+ \ell^- V$ Event Selection

The selection of $\ell^+ \ell^- V$ events is carried out in the following steps:

- (1) Events are required to have either four or six charged tracks, with total charge zero. Here a charged track is required to have at least four TPC coordinates and a point of closest approach to the beam axis which is within 2 cm of the beam, and within 5 cm of the interaction point along the beam axis. In addition it must make an angle of at least 18.2° with the beam axis. The sum of the energy of the charged tracks must be greater than 16 GeV to remove two-photon events. Four track events are rejected if there are more than two additional tracks which fail the above criteria but have at least three TPC coordinates. For six track

events, it is required that there be no such additional tracks. After these requirements are imposed 2699 events remain.

- (2) Most of these events are $Z \rightarrow \tau^+ \tau^-$ in which one or both τ s decay into three charged particles. To reject such events, all possible triplets of tracks with total charge ± 1 are formed and the number of triplets with invariant mass less than 1.7 GeV are counted. If there are four tracks it is required that there be no such triplets, and if there are six tracks it is required that there be one and only one such triplet. After this selection 248 events remain.

From this point on if there are six tracks the triplet is treated as a single charged particle with a four-momentum which is the sum of the three charged track momenta, where the particles are assumed to be pions. To take into account the bremsstrahlung of electrons and positrons, the energy of an associated ECAL cluster is used in place of the measurement from the ITC and TPC if the ECAL cluster energy is larger.

- (3) Most of the events with photons which convert in the material of the detector are removed as follows. Each track helix is projected onto the plane transverse to the beam direction. The triplet in the six track case is excluded. For each pair of oppositely charged tracks one finds the midpoint along the line segment joining the points where the tangents to the track projections are parallel. If the distance between the tangent points is less than 4 mm and the invariant mass of the pair is less than 50 MeV, assuming the tracks emanated from the midpoint, the event is rejected. This requirement leaves 83 events.
- (4) V candidates are formed from all pairs of oppositely charged tracks with an opening angle no larger than 120° , and where in addition the remaining two tracks (the lepton pair candidate) have an opening angle of at least 90° . The angular requirements help to reject hadronic Z decays and wrong combinations in $\ell^+ \ell^- V$ events. There are 61 events with at least one such V candidate.
- (5) For each V candidate in each event, the $V = e^+ e^-$, $\mu^+ \mu^-$, and $\pi^+ \pi^-$ mass hypotheses are used in turn to calculate the V four-momentum. For

each case the momentum and energy of the lepton pair candidate tracks are calculated in the Lorentz frame recoiling from the V. This frame should be the rest frame of the lepton pair in an $\ell^+\ell^-V$ event. The charged particles not making the V are required to be consistent with the hypothesis that they are a lepton pair or the decay products of a τ pair by satisfying the following criteria in this frame:

- $E_1/E > 0.05$ and $E_2/E > 0.05$, where $E_{1(2)}/E$ are the ratios of the lepton candidate energies to the calculated lepton energy. If this condition is not met, neutral energy in the ECAL in a cone of half-angle 18.2° around either charged particle direction is added vectorially to the charged particle energy and momentum and $E_{1(2)}$ are recalculated. This is done in order to retain efficiency for τ decays involving neutral pions.
- The acollinearity angle θ is required to satisfy $\theta < \theta_1 + \theta_2 + 2^\circ$, where $\theta_{1(2)}$ are the maximum angles which the decay product of a τ could make with the τ flight direction, given the decay product momentum (assuming it is an electron). The 2° allows for experimental resolution and the effect of initial state radiation.

There are 56 events with at least one V mass hypothesis satisfying these criteria. For each V mass hypothesis the lepton pair is classified as being a $\tau^+\tau^-$ candidate if one of the taus decays into three pions (6 track events), or if

$$E_1/E < 0.9, E_2/E < 0.9, \text{ and } (E_1+E_2)/E < 1.2.$$

Otherwise the lepton pair is classified as an e^+e^- or $\mu^+\mu^-$ candidate if

$$E_1/E > 0.8 \text{ and } E_2/E > 0.8.$$

Hypotheses failing both conditions are rejected. After this criterion 52 events remain having at least one mass hypothesis with a classifiable lepton pair.

- (6) After the above criteria there remains a background due to hadronic Z decays for the $\tau^+\tau^-V$ channel. This is reduced by requiring that the total estimated charged and neutral energy in the event does not exceed 80 GeV, using the technique described in Ref. [2]. This leaves 44 events.
- (7) Information on particle identification from the ECAL, HCAL, muon chambers, and energy loss in the TPC is used to make a unique assignment of particle type to all particles in the event. The V must be a particle-antiparticle pair. Three events fail this particle assignment: one $\tau^+\tau^-V$ and one $\mu^+\mu^-V$ in which the correct combinations fail the kinematic cuts due to a radiated photon, and one hadronic event. Four events have more than one V mass assignment. In such cases the candidate with the lowest mass is chosen.
- (8) As indicated below, some background remains at this point due to photon conversions; these populate the $V=e^+e^-$ case only. To remove this final source of background, for events with $V=e^+e^-$ it is further required that either the mass calculated at the parallel point described in criterion (3) be less than 20 MeV or be less than $100 \text{ MeV} \times (1-|\Delta_{xy}|)$, where Δ_{xy} (in cm) is the distance between the tracks projected onto the xy plane at the parallel point. This requirement removes six events, two in each lepton channel.

Table 1 lists the main properties for each of the 35 selected $\ell^+\ell^-V$ events. There are 10 e^+e^-V , 10 $\mu^+\mu^-V$, and 15 $\tau^+\tau^-V$ events in total. Figure 1 shows a typical four track event. Figure 2(a) shows the V mass distributions for the three lepton channels. We note that the $V=\pi^+\pi^-$ channel is peaked near the ρ mass. Figure 2(b) gives the $\ell^+\ell^-$ invariant mass distribution, as calculated from the V four-momentum, for the same events.

SECTION 3 - Background

The background to $\ell^+\ell^-V$ expected from known processes is estimated using Monte Carlo simulation.

(a) Hadronic Z decay.

A sample corresponding to 7.4×10^5 hadronic Z decays is used to estimate this source of background. Most of the events were selected to have low multiplicity before passing through the detector simulation. This represents four times the experimental sample. No event with four tracks passes the selection criteria but three events are found in the six track sample. We note, however, that they do not contain leptons, whereas all the six track events in the data have at least two leptons, though this is not required in the selection procedure. Twenty-nine events out of 740,000 pass selection criteria (1)-(5) but fail the total energy criterion (6) compared with 8 out of 185,000 in the data sample. This shows that the Monte Carlo is in good agreement with the data.

(b) Two photon process $e^+e^- \rightarrow e^+e^-$ hadrons.

For this process, events are preselected from a sample corresponding to 50 pb^{-1} . Events with at least 10 GeV of charged energy were passed through the detector simulation. No event passes the selection criteria.

(c) Lepton pair processes $Z \rightarrow e^+e^-(\gamma), \mu^+\mu^-(\gamma), \tau^+\tau^-(\gamma)$

The lepton pair events passing the selection criteria (1)-(7) all have $V=e^+e^-$ coming from converted photons which are not eliminated by criterion (3) of section 2 due to mismeasurement of the tracks. The events all have V masses below 400 MeV, and four are below 100 MeV. There are 3 $e^+e^-e^+e^-$, 2 $\mu^+\mu^-e^+e^-$, and 3 $\tau^+\tau^-e^+e^-$ events passing criteria (1)-(7) in 20 pb^{-1} generated according to the same E_{cm} distribution as the data. All the selected events fail criterion (8). The six events lost to criterion (8) in the data sample are in agreement with this: a loss of 3.4 ± 1.2 events is expected from the lepton-pair Monte Carlo and an

additional 1.5 ± 0.3 four-lepton events are expected to be lost, using the model described in the next section.

SECTION 4 - Comparison with Known Electroweak Processes

Production of $\ell^+\ell^-V$ events is expected in electron-positron annihilation through internal conversion of virtual photons emitted by the colliding electrons and final state leptons. The virtual photon materialises either as a lepton pair or as hadrons.

The pure QED process is calculated by Berends, Daverveldt and Kleiss [3], who have produced an event generator which is used here. The original generator was modified by Daverveldt to incorporate the Z diagrams [4]. This generator does not include initial or final state radiation, and uses a value of the electromagnetic coupling constant of $1/137$ at all vertices. Hence the cross sections calculated by the program are multiplied by an overall correction factor of 0.8.* For each of the final states $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$, $\tau\tau ee$, $\tau\tau\mu\mu$ and $\tau\tau\tau\tau$, 1500 events are generated at $E_{cm} = 91.2$ GeV and passed through the full detector simulation. Table 2 lists the calculated cross sections for the various final states.

The same generator has been used to evaluate the cross section for the production of two leptons and two pions. This is done by weighting each $\ell^+\ell^-\mu^+\mu^-$ event by the $\pi\pi$ to $\mu\mu$ ratio R measured in low energy e^+e^- annihilation [5]. ($R = F_\pi^2/4$ where F_π^2 is the time-like pion form factor). The result of this calculation is 30-50% greater than that expected on the basis of the calculations of Abraham and van der Bij [6] and of Bergstrom and Robinett [7]. We estimate the overall normalization of the pion-pair contribution to be accurate systematically within 30%.

The lack of initial and final state radiation in the generator affects the e , μ , and τ channels differently due to the selection procedure. The presence of a

* The factor 0.8 is $(137/128)^2 \times 0.7$, where the $137/128$ takes into account the proper value of the electromagnetic coupling constant at the Z for two of the vertices, and 0.7 is an approximation for the correction to the peak cross section due to initial state radiation.

high energy photon in the e and μ channels spoils the track-based kinematics, causing the event to be rejected by criterion (5) in section 2. For the τ channel these kinematic cuts have a smaller effect. The magnitude of the effect is estimated using a low-mass Higgs generator with and without initial and final state radiation. This results in a 10% reduction of the predicted e^+e^-V and $\mu^+\mu^-V$ rates, and a negligible change for the $\tau^+\tau^-V$ rate.

The expected numbers of events in the three lepton channels and in the three V decay channels are calculated and compared in Table 3 with the data. The above corrections are applied to the Monte Carlo predictions in the table and in all subsequent results. To correct for the fact that all the events are generated at the Z peak, the effective integrated luminosity at the peak is used. This underestimates the t -channel contribution, but as the efficiency is lower for low-angle events the change to the predicted e^+e^-V event rate is estimated to be no more than a few percent.

Several sources of statistical and systematic error in the relative predicted number of events can be identified. For example, the predicted number of $\ell^+\ell^-\pi^+\pi^-$ events depends on the relatively small number of $\ell^+\ell^-\mu^+\mu^-$ events in the Monte Carlo with V mass near the ρ , leading to a large statistical error. Together with the statistical precision of the other channels, the overall statistical precision of the predicted $\ell^+\ell^-V$ totals is 8%. Also, by changing the cut on charged energy from 16 GeV to 10 GeV, the lower limit on $E_{1(2)}/E$ from 0.05 to 0.03, the limit on $(E_1+E_2)/E$ from 1.2 to 1.4, and the cut on $\theta-\theta_1-\theta_2$ from 2° to 5° , no new events are selected, and the predicted ratio of $\tau^+\tau^-V$ to $\mu^+\mu^-V$ events increases by 8%. We note, however, that loosening these requirements increases the number of events in which wrong combinations must be rejected using particle identification. Taking into account these effects, the uncertainty from the detector simulation and calculated cross sections, we conservatively estimate the accuracy of the predicted $\ell^+\ell^-V$ totals relative to each other to be 20%.

Table 3 shows that while the number of observed events in the e^+e^-V and $\mu^+\mu^-V$ channels is somewhat greater than the prediction the number of $\tau^+\tau^-V$ events is considerably larger. For example, 15 $\tau^+\tau^-V$ events are observed but 3.2 events are expected. The relative predicted rate for $\tau^+\tau^-V$ is lower than the e^+e^-V and $\mu^+\mu^-V$ channels partly due to a lower cross section,

as shown in Table 2, and partly due to a lower efficiency due to the selection criteria.

Other features of the events are consistent with the model. The relative rates for $V=e^+e^-$, $\mu^+\mu^-$, and $\pi^+\pi^-$ are consistent with the expectation. Figure 3 shows the comparison of the data and the electroweak plus ρ prediction for several of the kinematic variables. The shape of the distributions show no substantial deviation from expectation. The observed V energy distribution shows the expected enhancement at low energies. The distribution of the angle θ_V between the lepton and the V direction shows a peak at small angles as expected for a dominantly radiative process.

The probability that the excess in the $\tau^+\tau^-V$ channel is due to a statistical fluctuation can be estimated in various ways. The predicted value of 3.2 is subject to a number of systematic errors resulting from uncertainties in the Monte Carlo generator, the sensitivity of the small sample of events to the cuts applied as well as the channel to channel variations described above. Our expectation is that the four lepton Monte Carlo will reproduce the absolute cross sections to approximately 30% whilst a comparison of this analysis with others using different cuts indicates these could contribute a further 30%. Adding these in quadrature yields a possible 45% correction for all channels. An increase of the prediction by this amount is in much better agreement with the observed numbers of e^+e^-V and $\mu^+\mu^-V$ events. Conservatively increasing this error by 20% to allow for the channel-to-channel variations yields an estimated systematic uncertainty for the $\tau^+\tau^-V$ channel of 65%. To calculate a probability we therefore increase the expected 3.2 events to 5.3 and determine the Poisson probability of observing 15 or more events when 5.3 are expected; this is 4×10^{-4} . Even more conservatively we can eliminate sensitivity to the absolute normalization by allowing it to float; we then find the probability of observing 15 or more $\tau^+\tau^-V$ events out of a fixed total of 35 is 8×10^{-4} when the fraction of $\tau^+\tau^-V$ events expected is 18.8% of the total. This probability increases to 4×10^{-3} if we in addition let the predicted $\tau^+\tau^-V$ fraction increase to 21.6% according to the above mentioned systematic error. We also note that if one asks what the probability is for a fluctuation to have occurred in any of the three channels, the above probabilities should be increased by a factor of three; the highest would thus become $\sim 1\%$.

It is important to point out that the efficiency for all three channels, and especially the $\tau^+\tau^-V$ channel, varies rapidly with decreasing angle θ_V , decreasing V energy, and decreasing V mass due to the triplet mass cut at 1.7 GeV and the pair conversion cut. The behaviour as a function of θ_V is illustrated in Figure 4. The predicted relative number of $\tau^+\tau^-V$ to $\mu^+\mu^-V$ events in the region where $\theta_V < 11.5^\circ$ is 20%, and for $\theta_V < 5^\circ$ this decreases further to 10%. Since the cross section increases as these three variables decrease, the expected number of events is sensitive to the exact balance between the two effects.

To avoid such uncertainties of acceptance we can make a check by examining the range where $\theta_V > 11.5^\circ$. The resulting numbers of events in each channel, together with the Monte Carlo predictions, are also shown in Table 3. There are 6 e^+e^-V , 8 $\mu^+\mu^-V$ and 14 $\tau^+\tau^-V$ events observed in this region; 5.8, 5.3, and 2.9 events are expected respectively. Calculating the probabilities as before, one finds 5×10^{-4} for observing 14 or more $\tau^+\tau^-V$ events when 2.9×1.65 are expected, 5×10^{-4} if the overall normalization is allowed to float, and 2×10^{-3} if the $\tau^+\tau^-V$ fraction is in addition increased by 20%. This indicates that the excess is not an artifact of poorly-modelled acceptance in the region of small θ_V .

To examine whether any structure exists in the V mass distribution, the error on the V mass can be estimated by propagation of the tracking errors, taking into account multiple scattering of the particles in the detector material. This method does not take into account final state radiation or bremsstrahlung, and hence tends to underestimate the real mass resolution, particularly in the case of $V=e^+e^-$. The four-lepton Monte Carlo can be used directly to estimate this (though not the effect of final state radiation), and shows that the V mass resolution for $V=e^+e^-$ is about ± 50 MeV with a non-gaussian tail, and about ± 12 MeV for $V=\mu^+\mu^-$ or $V=\pi^+\pi^-$. Assuming this resolution, inspection of the masses listed in Table 1(b) reveals no evidence for a narrow resonance as the source of the excess.

SECTION 5 - Conclusion

The selection of events from a sample of over 200,000 decays of the Z with the criteria described in Section 2 results in 10 e^+e^-V events, 10 $\mu^+\mu^-V$ events and 15 $\tau^+\tau^-V$ events. The observed shapes of the kinematic distributions are consistent with Monte Carlo simulation of four-lepton final states and ρ production. In addition the relative numbers of $V=e^+e^-$, $\mu^+\mu^-$, and $\pi^+\pi^-$ are also consistent with the radiation of virtual photons. However, an excess of events in the $\tau^+\tau^-V$ channel is observed [8]. The probability of a fluctuation having produced the excess depends on the reliability of the model and the detector simulation, but can be as large as 10^{-2} . The excess does not appear to populate $V=e^+e^-$, $\mu^+\mu^-$, or $\pi^+\pi^-$ preferentially.

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FIGURE CAPTIONS

- Fig. 1 A four track $\tau^+\tau^-V$ candidate (run 5166, event 981), where $\tau^+\rightarrow\mu^+\nu\bar{\nu}$ (track 1), $\tau^-\rightarrow\pi^-\nu$ (track 2) and $V\rightarrow\mu^+\mu^-$ (tracks 3 and 4).
- Fig. 2 (a) The distributions of invariant mass m_V of the pair forming the Vs. In each entry, the particle type of the pair forming the V is indicated. The distributions shown are for $Z\rightarrow e^+e^-V$, $Z\rightarrow\mu^+\mu^-V$ and $Z\rightarrow\tau^+\tau^-V$. The relative expected rates for these three channels is 1.1:1.0:0.5.
- (b) The distributions of the invariant mass of the lepton pair $m_{\ell\ell}$, for $Z\rightarrow e^+e^-V$, $Z\rightarrow\mu^+\mu^-V$ and $Z\rightarrow\tau^+\tau^-V$. Again, in each entry the particle type of the pair forming the V is indicated.
- Fig. 3 Comparison of observed e^+e^-V events and four-lepton and $\ell^+\ell^-\pi^+\pi^-$ Monte Carlo distributions
- (a) showing V mass m_V ;
 - (b) showing angle θ_V between V and lepton;
 - (c) showing V energy E_V ;
 - (d) showing V decay angle θ_D ;
 - (e) showing lepton pair mass (recoiling from the V).
- Fig. 4 The ratio of expected $\tau^+\tau^-V$ to $\mu^+\mu^-V$ events in the four-lepton Monte Carlo as a function of θ_V . (Here we exclude $V=\pi^+\pi^-$.)

TABLE 1(a)

Properties of Selected e^+e^-V and $\mu^+\mu^-V$ Events

Run	Event	E_{cm}	N_{trk}	E_{ch}	l^+l^-V	mV	$m_{\ell\ell}$	E_V	$m(3\pi)$	E_1/E	E_2/E	θ_1	θ_2	θ_{open}	θ_V	$\cos\theta_D$	E_{tot}	
1	8898	5940	91.2	4	86.0	ee	ee	0.341	47.22	33.39	6.87	0.94	0.92	-1.9	2.3	19.8	0.86	89.9
2	8960	749	88.2	4	61.0	ee	ee	1.454	84.77	3.39	8.60	1.24	0.95	-0.3	59.3	28.1	-0.55	90.8
3	9011	4093	91.2	4	83.3	ee	ee	2.297	72.50	16.82	4.63	0.87	0.94	-1.2	16.5	8.0	-0.31	89.1
4	7339	5121	91.2	4	83.5	ee	$\mu\mu$	3.457	65.67	22.05	5.68	1.01	0.98	-0.3	18.0	6.7	0.04	92.8
5	7849	456	91.2	4	95.3	ee	$\mu\mu$	22.996	49.15	35.27	43.04	1.01	1.11	0.1	93.9	83.1	-0.60	95.3
6	6975	1389	91.2	4	94.2	ee	$\pi\pi$	0.565	80.17	10.39	2.21	1.03	1.04	0.2	5.5	5.4	0.19	94.8
7	9010	5607	91.2	4	92.1	ee	$\pi\pi$	0.565	33.74	39.36	3.33	1.17	1.00	1.0	1.5	11.0	-0.45	92.1
8	7422	2873	91.2	4	89.9	ee	$\pi\pi$	0.590	50.61	31.57	23.91	0.98	0.95	0.7	1.9	63.1	-0.15	89.9
9	8163	2748	89.2	4	82.4	ee	$\pi\pi$	0.706	75.91	12.32	19.30	1.00	0.95	-0.3	7.2	55.8	-0.67	89.3
10	8334	7367	91.2	4	85.1	ee	$\pi\pi$	0.794	65.44	22.15	8.47	0.94	0.99	-0.8	4.2	21.7	0.44	89.8
11	7339	1745	91.2	4	90.5	$\mu\mu$	$\mu\mu$	0.135	89.26	1.95	3.19	1.01	0.98	-0.3	9.0	17.3	0.46	90.3
12	5825	51	91.5	4	80.5	$\mu\mu$	$\mu\mu$	1.063	55.65	28.85	30.14	0.95	0.99	1.3	4.4	75.2	-0.26	90.6
13	8855	3264	92.2	4	90.5	$\mu\mu$	$\mu\mu$	1.063	55.92	29.16	9.58	0.97	1.15	0.8	8.1	22.6	-0.86	93.0
14	8804	3691	90.2	4	84.1	$\mu\mu$	$\mu\mu$	1.232	76.17	12.96	3.02	0.96	0.89	-1.3	33.2	3.7	0.95	84.8
15	5821	3675	91.5	4	92.2	$\mu\mu$	$\mu\mu$	0.257	83.97	7.25	17.73	0.99	1.02	-0.1	2.3	62.7	0.30	92.2
16	4515	750	91.3	4	95.3	$\mu\mu$	$\mu\mu$	0.277	89.69	1.61	5.11	1.00	1.09	0.5	12.8	33.2	-0.22	91.6
17	8899	4745	91.2	4	90.5	$\mu\mu$	$\mu\mu$	2.288	76.14	13.86	4.69	1.00	0.98	-0.4	19.0	6.0	-0.07	90.5
18	8775	1605	91.2	4	88.6	$\mu\mu$	$\mu\mu$	8.329	75.78	14.52	28.54	0.97	0.96	-0.9	74.6	71.6	-0.39	90.0
19	8803	2443	90.2	4	90.2	$\mu\mu$	$\mu\mu$	38.855	36.57	46.06	50.19	1.03	0.91	1.0	115.1	77.9	0.07	90.8
20	7496	3332	91.2	4	90.9	$\mu\mu$	$\pi\pi$	0.811	58.77	26.68	5.88	0.99	1.01	-0.2	3.7	14.6	0.56	90.9

TABLE 1(b)

Properties of Selected $\tau^+\tau^-V$ Events

Run	Event	E_{cm}	N_{trk}	E_{ch}	l^+l^-	V	$\tau^+\tau^-$	$\tau^+\tau^-$	mV	m_{ll}	E_V	$m(3\pi)$	E_1/E	E_2/E	$\theta_1-\theta_2$	θ_{open}	θ_V	$\cos\theta_D$	E_{tot}
21	5509	2667	6	67.4	$\tau\tau$	ee	$3\pi\nu$	$\pi^+\pi^-\nu$	0.185	66.78	21.98	22.47	0.52	0.74	-2.3	1.0	75.7	-0.27	69.5
22	7743	8370	6	52.2	$\tau\tau$	ee	$3\pi\nu$	$\mu^+\nu$	0.402	83.43	7.46	17.36	0.41	0.66	-2.1	6.2	92.4	-0.05	70.2
23	7253	357	6	65.9	$\tau\tau$	ee	$3\pi\nu$	$\mu^+\nu$	0.833	83.90	6.11	8.86	0.50	0.97	1.3	17.0	32.2	0.38	78.3
24	7958	3841	6	49.4	$\tau\tau$	ee	$3\pi\nu$	$\rho^+\nu$	0.830	89.56	1.64	2.99	0.30	0.90	0.8	61.6	16.5	0.18	65.4
25	7681	2160	4	33.8	$\tau\tau$	ee	$e^+\nu$	$\pi^+\pi^-\nu$	1.072	71.00	15.55	3.29	0.17	0.61	-3.6	31.7	18.6	-0.97	62.8
26	8335	1133	4	43.1	$\tau\tau$	ee	$\rho^+\nu$	$e^+\nu$	1.819	76.96	13.17	2.08	0.67	0.37	-3.3	35.5	16.3	0.90	55.4
27	7858	8314	6	50.2	$\tau\tau$	$\mu\mu$	$3\pi\nu$	$\rho^+\nu$	0.484	56.25	27.58	17.63	0.10	0.94	-4.3	2.3	46.2	-0.84	68.0
28	5166	981	4	43.6	$\tau\tau$	$\mu\mu$	$\mu^+\nu$	$\pi^+\nu$	0.803	85.58	5.53	8.93	0.10	0.83	-3.8	18.3	37.2	-0.51	62.8
29	8623	158	4	28.6	$\tau\tau$	$\mu\mu$	$\pi^+\nu$	$\rho^+\nu$	1.187	68.39	19.98	8.55	0.74	0.17	-2.1	9.1	51.9	-0.69	61.8
30	8865	6111	4	17.7	$\tau\tau$	$\mu\mu$	$\mu^+\nu$	$e^+\nu$	1.275	82.62	8.20	4.31	0.09	0.14	-10.0	19.4	35.1	-0.43	22.4
31	8537	4398	4	40.4	$\tau\tau$	$\pi\pi$	$\pi^+\nu$	$\mu^+\nu$	0.694	87.39	3.76	3.68	0.59	0.23	-1.7	20.2	33.0	0.32	53.5
32	8833	4673	4	38.0	$\tau\tau$	$\pi\pi$	$\rho^+\nu$	$\rho^+\nu$	0.767	80.55	10.05	4.33	0.58	0.07	-1.9	8.3	48.7	-0.18	63.6
33	6972	4547	4	38.0	$\tau\tau$	$\pi\pi$	$\rho^+\nu$	$\pi^+\nu$	0.772	87.41	3.73	3.24	0.44	0.28	-2.9	32.1	18.3	0.86	41.7
34	8126	771	4	33.3	$\tau\tau$	$\pi\pi$	$e^+\nu$	$\rho^+\nu$	0.829	65.67	21.98	6.71	0.19	0.34	-6.4	4.1	37.6	0.19	48.5
35	8796	4675	4	39.3	$\tau\tau$	$\pi\pi$	$\rho^+\nu$	$\mu^+\nu$	1.022	83.03	7.82	2.15	0.65	0.15	-5.6	24.2	1.9	-0.88	66.5

Notation for Table 1

E_{cm}	centre-of-mass energy in GeV
N_{trk}	number of good charged tracks in event
E_{ch}	total charged energy of the event in GeV
m_V	invariant mass of the two particles forming the V in GeV
$m_{\ell\ell}$	invariant mass of the ($\ell\ell$) system in GeV
E_V	energy of the V in GeV
$m(3\pi)$	the smaller of the two invariant masses in GeV of the three charged particles which contain the two particles of the V
$E_1/E, E_2/E$	see Section 2
$\theta-\theta_1-\theta_2$	see Section 2
θ_{open}	opening angle of the two particles forming the V in the laboratory system in degrees
θ_V	angle between the V and the closest lepton ℓ in the laboratory system in degrees
$\cos\theta_D$	cosine of the V decay angle
E_{tot}	total energy in GeV of the events using the combined measurements of the TPC, ECAL and HCAL

TABLE 2

Calculated Four-lepton Cross Sections (Picobarns)

state ^a	m > 50 MeV ^b	m > 300 MeV
ee ee	1.30	0.57
ee $\mu\mu$	0.65	0.55
$\mu\mu$ ee	0.83	0.36
$\mu\mu\mu\mu$	0.45	0.39
$\tau\tau$ ee	0.65	0.33
$\tau\tau\mu\mu$	0.38	0.34

^a The second pair of particles in each state listed is the least massive oppositely charged pair of particles of the same type. The cross sections are calculated requiring all final state leptons to have an angle of at least 15° with the beam axis.

^b m = mass of lowest mass oppositely charged pair of particles of the same type

TABLE 3

TABLE 3
Comparison of Selected Events with Monte Carlo Predictions

Final State		all θ_V				$\theta_V > 11.5^\circ$			
		all m_V		$m_V > 2 \text{ GeV}$		all m_V		$m_V > 2 \text{ GeV}$	
		exp ^a	obs ^b	exp	obs	exp	obs	exp	obs
ee	ee	2.2	3	0.4	1	1.8	2	0.4	0
ee	$\mu\mu$	2.0	2	0.4	2	1.7	1	0.3	1
ee	$\pi\pi$	3.0	5	0.0	0	2.4	3	0.0	0
ee total		7.2	10	0.8	3	5.8	6	0.8	1
$\mu\mu$	ee	2.0	4	0.3	0	1.6	3	0.3	0
$\mu\mu$	$\mu\mu$	1.8	5	0.4	3	1.5	4	0.4	2
$\mu\mu$	$\pi\pi$	2.8	1	0.0	0	2.2	1	0.0	0
$\mu\mu$ total		6.6	10	0.7	3	5.3	8	0.7	2
$\pi\pi$	ee	1.1	6	0.2	0	1.0	6	0.2	0
$\pi\pi$	$\mu\mu$	0.9	4	0.2	0	0.8	4	0.2	0
$\pi\pi$	$\pi\pi$	1.2	5	0.0	0	1.1	4	0.0	0
$\pi\pi$ total		3.2	15	0.5	0	2.9	14	0.4	0
grand total		17.0	35	2.0	6	14.0	28	1.8	3

^a exp = expected number of events from electroweak processes

^b obs = observed number of events

ALEPH

$$\tau^+\tau^- \rightarrow \mu^+\mu^- \quad (4,3)$$

$$\tau^+\tau^- \rightarrow \mu^+\nu\bar{\nu} \quad (1)$$

$$\tau^-\tau^+ \rightarrow \pi^-\nu \quad (2)$$

$$M_V = 803 \text{ MeV}$$

Fig. 1

Fig. 2(b)

Fig. 3

Fig. 3

Fig. 3

Fig. 4