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A 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*

THE MARK II (AT PEP) COLLABORATION

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Conf-9107172--1

ABSTRACT

We have searched for the reaction $e^+e^- \to \tau^+\tau^- ff$, where f is either an electron, muon, or charged pion, at $\sqrt{s} = 29$ GeV using the Mark II detector at the PEP storage ring. 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 $e^+e^- \to \tau^+\tau^- ff$ 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 $e^+e^- \to e^+e^- ff$ and $e^+e^- \to \mu^+\mu^- ff$, and for $e^+e^- \to \tau^+\tau^-\gamma$ using a similar analysis procedure and see the number of events predicted by the standard model.

DISCLAIMER

INTRODUCTION

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

$$e^+e^- \to \tau^+\tau^- ff, \quad f = e^-, \mu^-, \pi^+ ,$$

at $\sqrt{s} = 91$ GeV.[1] An excess of $\tau^+\tau^- ff$ events is seen in comparisons both of the observed number of $\tau^+\tau^- ff$ events with the standard model prediction for the absolute rate and of the number of $\tau^+\tau^- ff$ events relative to $e^+e^- ff$ and $\mu^+\mu^- ff$ events.

In previous papers we showed that the reactions

$$e^+e^- \to e^+e^-e^+e^-$$
$$e^+e^- \to e^+e^-\mu^+\mu^-$$
$$e^+e^- \to \mu^+\mu^-\mu^+\mu^-$$

proceed at the rate predicted by the standard model at $\sqrt{s} = 29$ GeV[2] as does the reaction $\tau^+\tau^-\gamma$.[3] In this paper we report on a search for events of the type $\tau^+\tau^- ff$ 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 at PEP

The Mark II detector has been described previously.[4] In this analysis we use the tracking system consisting of a sixteen layer cylindrical drift chamber and a seven layer vertex drift chamber to measure charged particle momenta. These systems covered the central 85% of the solid angle. We use the lead-liquid argon electromagnetic calorimeter to measure the energies of photons and to correct the momenta of electrons. This detector covered 65% of the solid angle.

Selecting tracks

Charged tracks must have a momentum in the plane perpendicular to the beam axis greater than 0.08 GeV/c. The distance between the track and the average collision point must be less than 1 cm in the plane perpendicular to the beam axis, and less than 3 cm parallel to the axis. These requirements help ensure that the tracks are well measured and that their efficiency is understood.

We set the momentum of a charged track equal to the measured drift chamber momentum with one exception: if the charged track is identified as an electron,[5] and the associated calorimeter energy exceeds the drift chamber momentum, we set the charged track's momentum equal to its calorimeter energy. Due to radiation, this is usually the better measurement.

An energy cluster in the calorimeter is treated as an independent neutral track if it has an energy greater than 0.2 GeV (to ensure good efficiency) and is not associated with a charged track by the calorimeter cluster reconstruction algorithm.

Selecting events

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.[6]

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 GeV 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 $e^+e^- \rightarrow \tau^+\tau^- f\bar{f}$. We note here that the following selection procedure was tuned on a sample of $\tau^+\tau^-\mu^+\mu^-$ Monte Carlo[7] 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 tau decay products and to the f and $\bar{f}$. We call such an assignment of tracks a "$\tau^+\tau^- f\bar{f}$ configuration." We try all possible $\tau^+\tau^- f\bar{f}$ configurations and keep the one that is most consistent with the reaction $e^+e^- \rightarrow \tau^+\tau^- f\bar{f}$.

To produce a $\tau^+\tau^- f\bar{f}$ configuration we first assign one charged track to the f and another to the $\bar{f}$. 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. For the purpose of calculating the mass of the V, the masses of the f and $\bar{f}$ tracks are set equal to the electron mass. 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 the tracks in this frame and the tracks are then grouped according to thrust hemispheres. If after this grouping the net charge of each thrust hemisphere is not ± 1 the $\tau^+\tau^- ff$ 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 in thrust hemisphere i, $i = 1,2$. In forming p_i the mass of charged tracks is set equal to the charged pion mass. 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 tau 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. The distribution of the mass of this τV combination from our $\tau^+\tau^-\mu^+\mu^-$ simulation is shown in Figure 1.

In order to further reduce hadronic background we keep only configurations for which the tau 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 1). For example, if thrust hemisphere i contains one charged track and one neutral track then the maximum allowed value for m_i is 1.2 GeV/c^2 while if the hemisphere contains one charged track and greater than two neutral tracks then m_i must be less than 1.9 GeV/c^2. Figure 2 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 tau's energy that goes into visible decay products.

The primary purpose of cutting on this variable is to remove background from $e^+e^- \rightarrow e^+e^-f\bar{f}, \mu^+\mu^-f\bar{f}$. As a consequence, the cut on η_i will be harder for leptonic tau decays than for hadronic tau 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 an "hadronic decay." Note that with this scheme tau 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" tau 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" tau 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" tau 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". Monte Carlo calculations predict that there should be less than 0.03 events from $e^+e^- \rightarrow \tau^+\tau^-$[8] and $e^+e^- \rightarrow e^+e^-f\bar{f}, \mu^+\mu^-f\bar{f}$ with at least one valid $\tau^+\tau^-f\bar{f}$ configuration, while there should be 3.1±0.1 events from $e^+e^- \rightarrow \tau^+\tau^-f\bar{f}$ with at least one valid $\tau^+\tau^-f\bar{f}$ configuration. Hadronic Monte Carlo[9] calculations predict, however, that there will be 28 events from $e^+e^- \rightarrow q\bar{q}$ which contain at least one valid $\tau^+\tau^-f\bar{f}$ configuration.

To remove the remaining hadronic events we calculate the square of the missing mass in each tau decay and compare it with the distribution predicted by the $\tau^+\tau^-f\bar{f}$ Monte Carlo. "Hadronic" tau decays have a missing mass squared of zero, within experimental resolution, and the spectrum for the missing mass squared of "leptonic" tau decays is broader with the mean shifted to a small positive value. Hadronic events tend to produce large negative values for the missing mass squared because the assumption that tracks come from the decay of a τ is wrong.

Let $M_{\nu 1}$ and $M_{\nu 2}$ be the missing masses for the tau decays in thrust hemispheres 1 and 2 respectively. Let θ and ϕ be the polar and azimuthal angles of the tau lepton in hemisphere 1 in the $\tau^+\tau^-$ candidate rest system. Figure 3 contains the distributions in $M^2_{\nu 1}$ for $e^+e^- \to \tau^+\tau^-\mu^+\mu^-$ Monte Carlo events. Full detector simulation has been used in calculating $M^2_{\nu 1}$ in Fig. 3 with the exception that θ and ϕ are taken directly from the Monte Carlo generator. Figure 3(a) shows the distribution of $M^2_{\nu 1}$ for hadronic tau decays and Fig. 3(b) shows the distribution for leptonic decays. As before, hadronic and leptonic decays of the tau are distinguished by the mass of the visible decay products: if the visible mass is less than 0.15 GeV/c^2 the decay is "leptonic," otherwise it is "hadronic."

Let $f_H(M^2_{\nu 1})$ be the distribution in $M^2_{\nu 1}$ for "hadronic" tau decays, and $f_L(M^2_{\nu 1})$ be the distribution in $M^2_{\nu 1}$ for "leptonic" tau decays. They are normalized such that their peak values are 1.0. Since θ and ϕ are unknown we let them vary and find those values which yield the maximum of the joint probability of $M^2_{\nu 1}$ and $M^2_{\nu 2}$. Let

$$\psi \equiv \max_{\substack{0 \leq \theta \leq \pi \\ 0 \leq \phi \leq 2\pi}} f_1(M^2_{\nu 1}(\theta,\phi))\, f_2(M^2_{\nu 2}(\theta,\phi))$$

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

We define Ψ to be the maximum value of ψ over all valid $\tau^+\tau^- ff$ configurations in an event. Figure 4a 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. 4b. Nearly all $\tau^+\tau^-\mu^+\mu^-$ events have Ψ very close to 1, whereas nearly all hadronic events have Ψ very close to 0. 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 4c shows the distribution of Ψ from the data. There are 7 events in our data with Ψ close to 0, and 1 event, our lone $\tau^+\tau^- ff$ candidate, with $\Psi = 0.71$.

Figure 5 is an event picture of our one $\tau^+\tau^- ff$ candidate. There are two valid $\tau^+\tau^- ff$ configurations for this event with ψ greater than 0.3. In one configuration the V is made of tracks 3 and 4, the mass of the V is 0.115 GeV/c^2 and $\psi = 0.69$. In the other configuration the V is made of tracks 2 and 4, the mass of the V is 1.9 GeV/c^2 and $\psi = 0.71$. Interpreting the event as $e^+e^- \to \tau^+\tau^- f\bar{f}$ we see that each tau decays to a charged pion and several neutral pions. The visible mass of each tau, in each configuration, is 1.5 GeV/c^2.

Table 2 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

We would now like to check our efficiency and cross-section calculations for $e^+e^- \to \tau^+\tau^- f\bar{f}$. One way to do this is to modify 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 events 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 (Ref. 8), 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 $e^+e^- \to e^+e^- f\bar{f}, \mu^+\mu^- f\bar{f}$ is identical to the one for $e^+e^- \to \tau^+\tau^- f\bar{f}$.

There are 65 data events which pass our cuts for $e^+e^- \to e^+e^- f\bar{f}, \mu^+\mu^- f\bar{f}$. Table 3 shows the expected number of events from various processes. In total there are 62.2 events expected from all processes in Table 3.

CONCLUSION

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}. While ALEPH expects to see 1.3 times as many events as we do, they in fact observe 14 events to our 1. If we hypothesize that there is a universal enhancement of the $\tau^+\tau^- f\bar{f}$ process we would still expect to see a 1.3:1 ratio of events between experiments. Using binomial statistics we calculate that the probability of getting a ratio of events as far or farther from 1.3:1 than 14:1 is 0.005.[10]

REFERENCES

1. ALEPH Collaboration, *Phys. Lett.* **B263** (1991), 112. ALEPH reports seeing 14 events where they expect 3.
2. M. Petradza et al., *Phys. Rev.* **D42** (1990), 2171. This paper treated final states with charged particle pair masses greater than 0.6 GeV/c^2.
3. D. Y. Wu et al., *Phys. Rev.* **D41** (1990), 2339. This study emphasized photons radiated from the tau leptons.
4. R. H. Schindler et al., *Phys. Rev.* **D24** (1981), 78.
5. The electron identification algorithm depends on a comparison of the energy deposited in the layers of the calorimeter to the momentum measured by the tracking system. The cuts used roughly correspond to an E/p of 0.8. See R A. Ong, Ph.D. thesis, SLAC–0320, unpublished.
6. 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–16724, 1983, unpublished.
7. This sample, and all other four lepton final state samples used in this paper, were generated with the Monte Carlo program written by Berends, Daverveldt, and Kleiss which is described in Berends et al., *Nucl. Phys.* **B253** (1985), 441.
8. We use the Monte Carlo Koralz3 (S. Jadach, B. F. L. Ward, preprint CERN-TH–5994–91, 1991) to simulate $\tau^+\tau^-$ and $\tau^+\tau^-\gamma$ production.
9. This number, and others from the hadronic Monte Carlo, are sensitive to the details of the generator. We use JETSET 6.3. See A. Petersen, *Phys. Rev.* **D37** (1988), 1, for a complete description. This Monte Carlo is used only for tuning cuts. It is not used in obtaining the result in any other way.
10. This is the two sided confidence level, i.e., it is twice the probability for getting a ratio $\geq$ 14:1 given 15 total events for both experiments.

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

Table 1. Hemisphere mass cut.

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

Table 2. Expected events from known processes.
Items within parentheses are not included in the total.

Process	Number of events expected to pass $e^+e^-f\bar{f}$ or $\mu^+\mu^-f\bar{f}$ selection
$e^+e^- \rightarrow e^+e^-e^+e^-$	28.1
$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$	23.4
$e^+e^- \rightarrow e^+e^-q\bar{q}$	7.7
$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$	2.3
$e^+e^- \rightarrow \mu^+\mu^-q\bar{q}$	0.7
$e^+e^- \rightarrow q\bar{q}$	0
$e^+e^- \rightarrow \tau^+\tau^-$	0
$e^+e^- \rightarrow e^+e^-\tau^+\tau^-$	0.1
Total	62.2

Table 3. Expected events for $e^+e^-f\bar{f}$ and $\mu^+\mu^-f\bar{f}$ analysis.

FIGURE CAPTIONS

1) Mass of the τV combination from the $\tau^+\tau^-\mu^+\mu^-$ simulation. The arrow indicates the location of the cut.

2) 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, e) 3 charged tracks, ≥ 1 neutral track. The arrows indicate the locations of the cuts.

3) Missing mass squared distributions: a) "hadronic" τ decays, b) "leptonic" τ decays.

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

5) $\tau^+\tau^-f\bar{f}$ candidate.

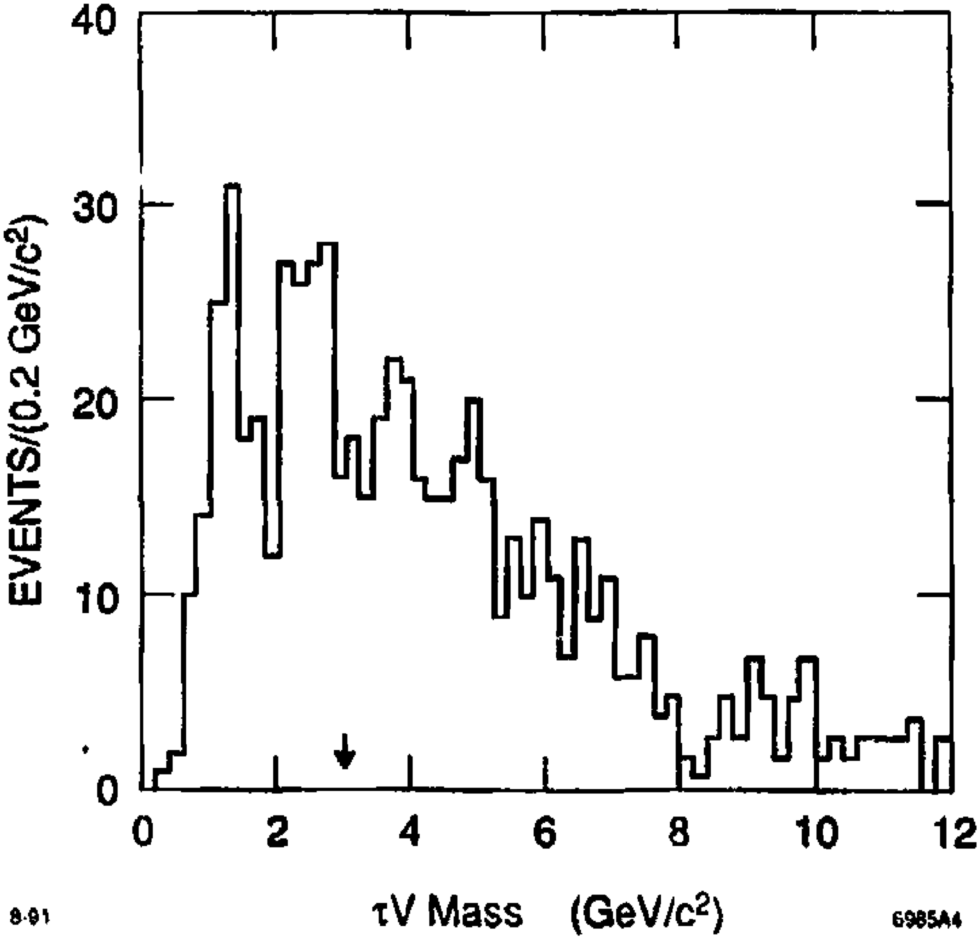

40
30
20
10
0
EVENTS/(0.2 GeV/c²)
0
2
4
6
8
10
12
8-91
τV Mass (GeV/c²)
6985A4

Fig. 1

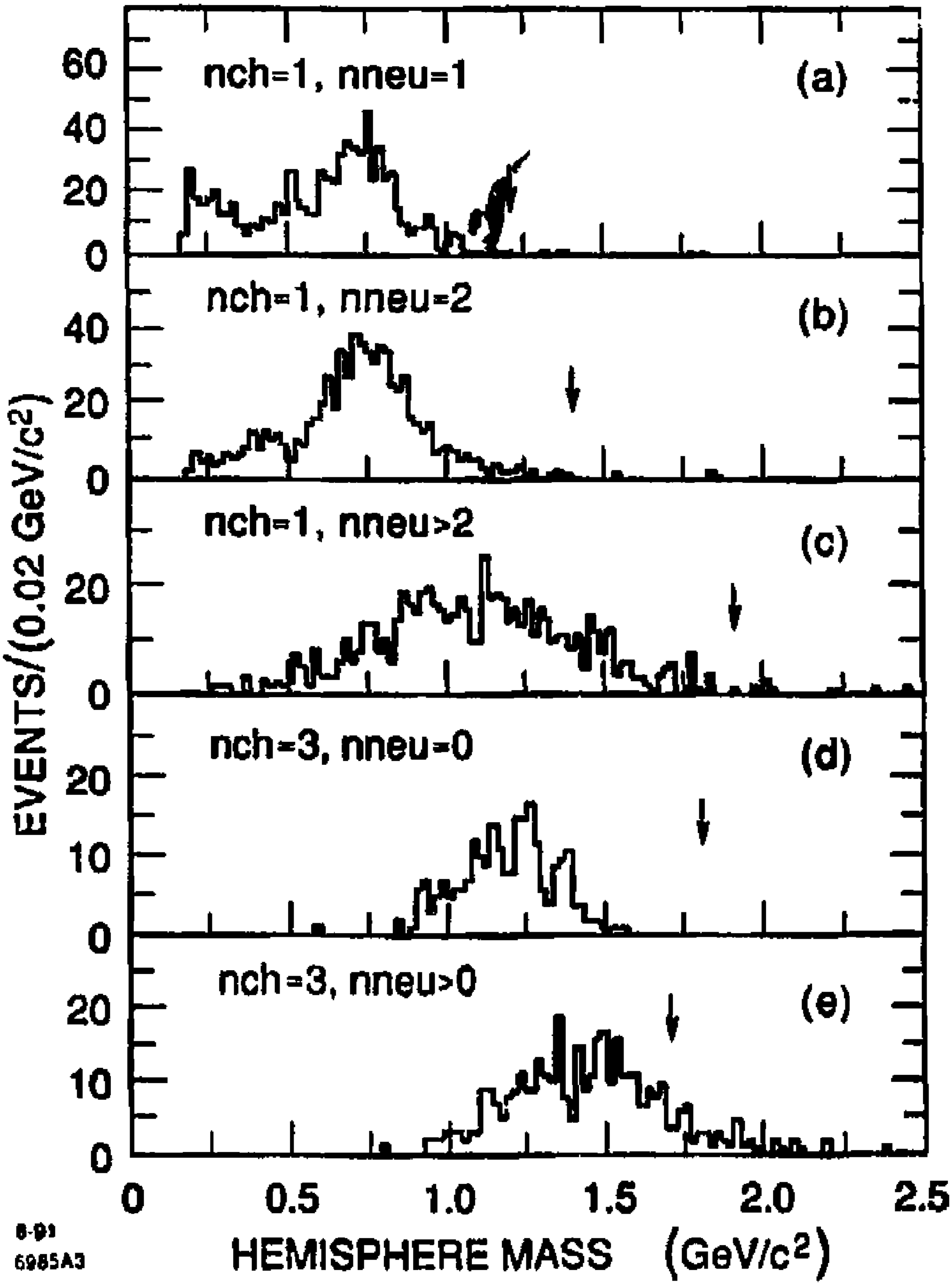
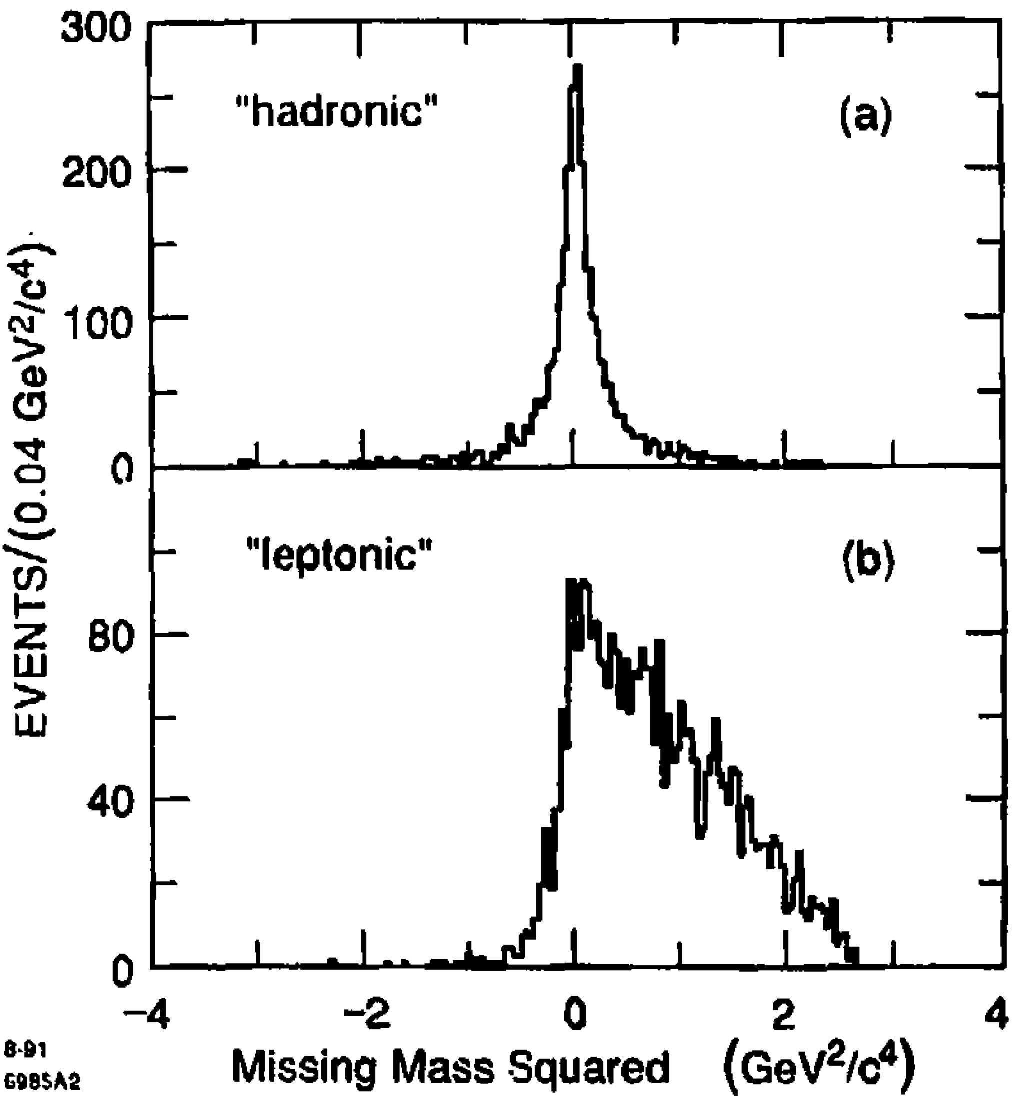
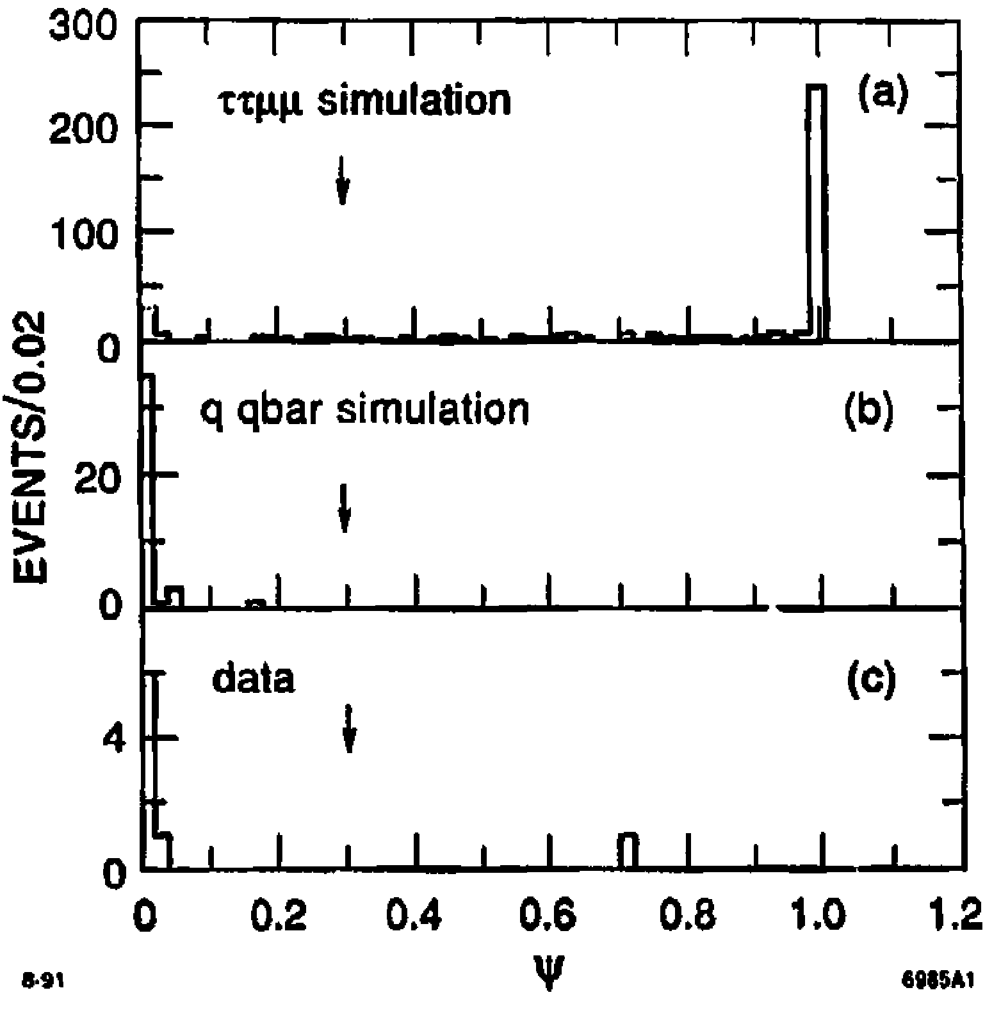

nch=1, nneu=1
(a)
nch=1, nneu=2
(b)
nch=1, nneu>2
(c)
nch=3, nneu=0
(d)
nch=3, nneu>0
(e)
EVENTS/(0.02 GeV/c2)
HEMISPHERE MASS (GeV/c2)
0
0.5
1.0
1.5
2.0
2.5
8-91
6985A3

Fig. 2



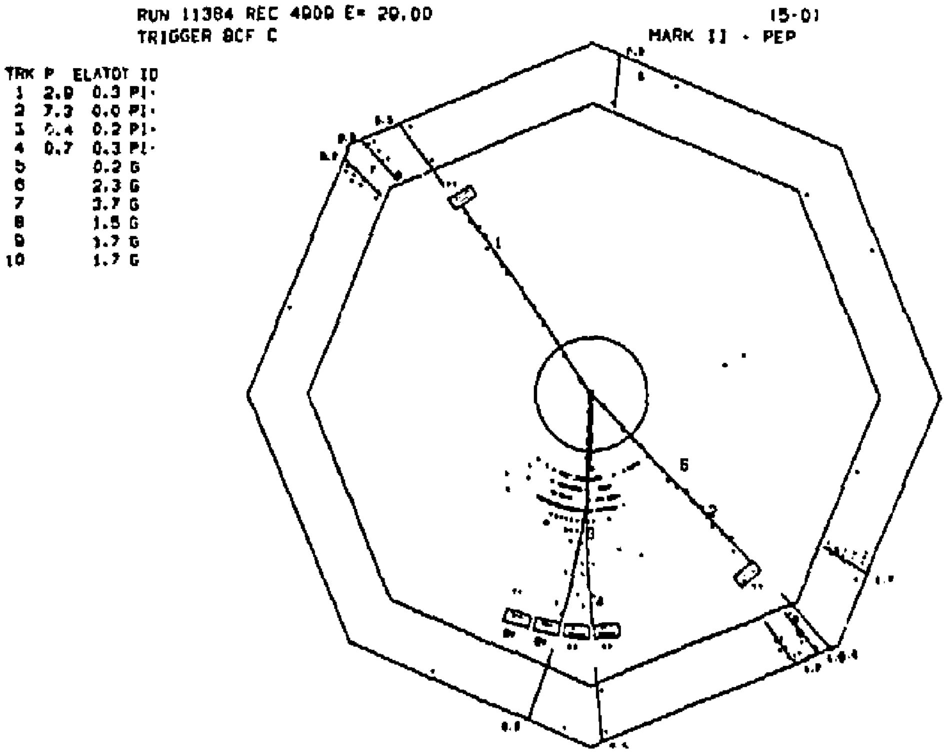
300
200
100
0
80
40
0
"hadronic"
(a)
"leptonic"
(b)
EVENTS/(0.04 GeV²/c⁴)
−4
−2
0
2
4
Missing Mass Squared (GeV²/c⁴)
8-91
6985A2

Fig. 3



300
200
100
0
20
0
4
0
ττμμ simulation
(a)
q qbar simulation
(b)
data
(c)
EVENTS/0.02
0
0.2
0.4
0.6
0.8
1.0
1.2
ψ
8-91
6985A1

Fig. 4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TRIGGER 8CF C
15-01
MARK II - PEP
TRK P ELATOT ID
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2 7.3 0.0 PI-
3 0.4 0.2 PI-
4 0.7 0.3 PI-
5 0.2 G
6 2.3 G
7 3.7 G
8 1.5 G
9 1.7 G
10 1.7 G
1
6

Fig. 5