# SLAC-207 UC-34d (T/E)

# ANOMALOUS ELECTRON-MUON AND ELECTRON-HADRON PRODUCTION IN ELECTRON-POSITRON ANNIHILATION\*

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### ABSTRACT

Results of studies of anomalous electron-muon and electron-hadron events produced in electron-positron annihilation are presented. The data for this work were obtained with a lead-glass counter system, which was added to one octant of the Stanford Linear Accelerator Center-Lawrence Berkeley Laboratory magnetic detector at the electron-positron storage ring SPEAR. The lead-glass counter system provides good electron identification for part of the magnetic detector.

The events under study have two detected charged particles and any number of detected photons. One detected charged particle is identified as an electron in the lead-glass counter system. The other detected charged particle is identified as a muon or hadron in the magnetic detector. Anomalous events are events which are not subject to conventional explanations; examples of conventional explanations are misidentification of particles or the decay of ordinary or strange hadrons.

These data confirm previous observations of anomalous lepton production at SPEAR and DESY. The data corrected for charm background are consistent with heavy lepton production and decay. The branching ratio for the heavy lepton to decay into an electron and two neutrinos was measured to be  $0.21 \pm 0.05$ . The branching ratio for the heavy lepton to decay into one charged hadron, one neutrino and any number of photons was measured to be  $0.28 \pm 0.13$ . They are consistent with the theoretical values within the errors.

\* Ph.D. dissertation.

### TABLE OF CONTENTS

Page

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1.	INTRODUC	FION .	٠	••	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	1
11.	THEORY .		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	3
111.	SUMMARY (	OF PRE	VIO	US	RE	ទហ	TS	;	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	8
IV.	APPARATU	s	. •		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	35
۷.	ANALYSIS		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	56
VI.	RESULTS		•	• •	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	75
VII.	CONCLUSI	ONS .	•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	100
APPEN	DIX A: S	HOWER	cou	NTE	R	CAI	LIH	BRA	ΤI	ON		•	•	•	•	•	•	•	•	•	•	•	•	101
APPEN	DIX B: S	HOWER	COU	NTE	R	EFI	FIC	CIE	NC	Y	•	•	•	•	•	•	•	•	•	•	•	•	•	104
APPEN	DIX C: M	ATRIX	OF	MIS	ID	EN	<b>FI</b>	FIC	AT	10	N	PR	OE	SAF	11	LI.	C 1 ]	zs	٠	•	•	•	•	110
REFER	ENCES		•	•	•	•	•	•	•	•	•	•	•	•	•		•	•	•	٠	٠	•	•	112

iv

# LIST OF TABLES

.

n the lead-glass zero and (B) charge ons. in (A) the lead-glass detector as described ) charge ±2 two-prong
zero and (B) charge ons. in (A) the lead-glass detector as described ) charge ±2 two-prong
zero and (B) charge ons. in (A) the lead-glass detector as described ) charge ±2 two-prong
ons. in (A) the lead-glass detector as described ) charge ±2 two-prong
in (A) the lead-glass detector as described ) charge ±2 two-prong
detector as described ) charge ±2 two-prong
) charge ±2 two-prong
) charge ±2 two-prong
on, but not corrected
ic acceptances or
istical.
ef. 29), (B) the semi-
ef. 28) and (C) the
D (Ref. 29) in the
the contribution to
charm production.
on to the anomalous
semileptonic decay of
ns for eµ events,
E <sub>cm</sub> regions before
on. The cross sec-
ation, but not cor-
geometric acceptance
tatistical.

vi

÷,

Page

57

63

66

72

76

83

Page

94

108

Page

86

87

88

91

93

- XVII. The point particle pair production cross section,  $\sigma_{\tau\tau}$ , for a heavy lepton  $\tau$  with  $m_{\tau} = 1.85 \text{ GeV/c}^2$  in four  $E_{cm}$  regions.
- XVIII. The acceptances  $A_{e\mu}$  and  $A_{eh}$ , which include triggering efficiencies, geometric acceptances and kinematic cuts, for eµ and eh events respectively, in four  $E_{cm}$  regions. The assumptions used for the calculation of the acceptances are described in the text.
  - XIX. The branching ratio  $B_e$  and  $B_h$  for  $\tau \rightarrow v_{\tau} e \overline{v}_e$  and  $\tau \overline{\phantom{v}} \rightarrow h \overline{\phantom{v}} + v_{\tau} + \ge 0$  y's respectively before and after charm background subtraction. The assumptions used for the calculation of the branching ratios are described in the text. The errors are statistical.
  - XX. The estimated maximum systematic errors on the branching ratios  $B_{p}$  and  $B_{h}$ . 89
  - XXI. The fractions of events as described by Eq. (58) where both photons escape detection.
- XXII. The number of eh events without photons and the observed production cross section for eh events without photons corrected for misidentification and the background described in Sec. VIC, but not corrected for triggering efficiencies, geometric acceptances or kinematic cuts. The errors are statistical.
- XXIII. The number of eu events with photons and the observed production cross section for eu events with photons corrected for misidentification and the background described

in Sec. VID, but not corrected for triggering efficiencies, geometric acceptances or kinematic cuts. The errors are statistical.

XXIV. The shower counter cosmic ray efficiency in each shower counter for the full counter length and counter width. Counters 12, 13 and 14 are scintillation counters. The efficiencies averaged over all the shower counters are (A) 0.967 for the fall cycle data and (B) 0.930 for the spring cycle data.

vii

#### LIST OF FIGURES

Page

10

12

- 1. The r distribution for everents from the SLAC-LBL Magnetic Detector Collaboration in the  $E_{cm}$  region of 3.8 to 7.8 GeV. The distribution has been corrected for background. The solid curve is for the 3-body, leptonic decay of the  $\tau$  with the indicated parameters. The dash and dash-dot curves are for the 2-body leptonic decay modes of a boson; the former is for no spin alignment of the boson, and the latter is for a spin 1 boson produced only in the helicity = 0 state. (Refs. 1, 3, 14)
- The r distributions for eµ events from the SLAC-LBL Magnetic Detector Collaboration in three E<sub>cm</sub> regions. The distributions have been corrected for background. See the caption to Fig. 1. (Refs. 1, 3, 14)
- 3. The  $\cos \theta_{coll}$  distributions for ep events from the SLAC-LBL Magnetic Detector Collaboration in three  $E_{cm}$  regions. The distributions have been corrected for background. The solid curve is for  $m_{\tau} = 1.9 \text{ GeV/c}^2$ ,  $m_{\nu_{\tau}} = 0.0$  and V-A coupling. (Refs. 1, 3, 14)
- 4. The observed eµ production cross section  $\sigma_{e\mu}$  vs.  $E_{cm}$  for eµ events from the SLAC-LBL Magnetic Detector Collaboration. The vertical lines are statistical errors. The horizontal lines show the  $E_{cm}$  range covered by each point. No events <u>before</u> background subtraction were found in the  $E_{cm}$  range of 3.0 to 3.6 GeV. We show the 90% confidence

upper limit on  $\sigma_{e\mu}$  if 2.3 events had been found. The curves are for  $m_{\tau} = 1.8$  or 2.0 GeV/c<sup>2</sup>. The product  $B_{e\mu}^{B}$  is adjusted for each mass choice to give the best fit. The  $\chi^2$  probability of these fits is 90%. (Refs. 1, 3, 14)

- 5. The electron momentum distribution for eµ events from the PLUTO Group in the  $E_{cm}$  region of 4.0 to 5.0 GeV. The distribution has been corrected for trigger and detector acceptance, hadron punchthrough and electron detection efficiency. The solid curve is calculated for V-A coupling,  $m_{\tau} = 1.91 \text{ GeV/c}^2$  and  $m_{v_{\tau}} = 0$ . Note that the detection efficiency distorts the lower part of the spectrum. (Refs. 8, 10, 13)
- 6. The muon production cross section vs.  $E_{CM}$  for (a) inclusive two-prong  $\mu x$  events, (b) inclusive multiprong muon events and (c) exclusive  $\mu e$  events from the PLUTO Group. The cross sections are given for muon momenta greater than 1 GeV/c. They have been corrected for trigger and detector acceptance, and for hadron punchthrough. Part (a) has also been corrected for backgrounds from quantum electrodynamic processes. Part (c) has also been corrected for electron detection efficiency. The solid curves are calculated for V-A coupling,  $m_{\tau} = 1.91 \text{ GeV/c}^2$  and  $m_{V_{\tau}} = 0$ . (Refs. 8, 10, 13)
- 7. The muon momentum distributions for (a) two-prong  $\mu x$  events and (b) multiprong muon events from the SLAC-LBL Magnetic Detector Collaboration in the E<sub>cm</sub> region of 5.8 to 7.8 GeV.

ix

x

Page

13

14

Page

18

The solid curve represents the expected cross section for a heavy lepton with a V-A decay, a branching fraction to  $\mu\nu\bar{\nu}$  of 0.17, and a mass between 1.6 and 2.0 GeV/c<sup>2</sup>. (Refs. 2, 3. 14)

- 8. The muon momentum distributions for two-prong  $\mu x$  events from the PLUTO Group in three  $E_{cm}$  regions. The cross sections have been corrected for trigger and detector acceptance, hadron punchthrough and backgrounds from quantum electrodynamic processes. The fits assume V-A coupling,  $m_{\tau} = 1.91 \text{ GeV/c}^2$  and  $m_{\nu_{\tau}} = 0$ . (Refs. 9, 10, 13) 19
  - 9. The electron momentum distribution for two-prong ex events from the DASP Group in the  $E_{cm}$  region of 4.0 to 5.2 GeV. The fit assumes V-A coupling,  $m_{\tau} = 1.90 \text{ GeV/c}^2$  and  $m_{\nu_{\tau}} = 0$ . (Refs. 11, 12, 13) 21
- 10. The electron production cross section vs.  $E_{cm}$  for twoprong ex events from the DASP Group.  $A_{ex}$  is the acceptance of the apparatus for ex events. The fit assumes V-A coupling,  $m_{\tau} = 1.80 \text{ GeV/c}^2$  and  $m_{v_{\tau}} = 0$ . (Refs. 11, 12, 13) 22 11. The electron momentum distribution for two-prong ex events from the DELCO Group in the  $E_{cm}$  region of 3.8 to 5.0 GeV.
- The curve is a theoretical Monte Carlo calculation for the 3-body leptonic decay of a mass 1.85 GeV/c<sup>2</sup>  $\tau$ . (Ref. 5) 23 12. The electron production cross section ratio  $r_e$  (eq. 22) vs.  $E_{cm}$  for two-prong ex events from the DELCO Group. The

curve shows the expected smooth yield from a heavy lepton pair with a branching ratio of 0.15 to  $v_{\tau} = \bar{v}_{\mu}$ . (Ref. 5) 24

- 13. The P<sub>1</sub> distribution for eµ events from the SLAC-LBL Magnetic Detector Collaboration with  $E_{cm} > 4.8$  GeV. The distribution has been corrected for contamination by background events. The solid line is a theoretical calculation of this distribution for a lepton with  $m_{\tau} = 1.90$  GeV/c<sup>2</sup>,  $m_{\nu_{\tau}} = 0.0$  and V-A coupling. (Refs. 1, 3, 14)
- 14. The r distribution for all eµ events from the SLAC-LBL Magnetic Detector Collaboration. The distribution has been corrected for background. The solid curves are for  $m_{\tau} = 1.90$  GeV/c<sup>2</sup>, V-A Coupling, and  $m_{v_{\tau}}$  in GeV/c<sup>2</sup> as indicated. The dashed curve is for V + A coupling,  $m_{\tau} = 1.90$  GeV/c<sup>2</sup> and  $m_{v_{\tau}} = 0.0$ . (Refs. 1, 3, 14) 28
- 15. The ratio  $R_{2pr}$  (eq. 26) vs.  $E_{cm}$  for  $e^+e^- + 2$  prong events with radiative corrections from the PLUTO Group. The curve indicates the contribution to  $R_{2pr}$  from a heavy lepton with a mass of 2.0 GeV/c<sup>2</sup>. The different symbols represent data taken at different times. (Ref. 22) 34
- 16. The layout of the SPEAR e<sup>+</sup>e<sup>-</sup> colliding beams facility. 36
  17. An exploded view of the SLAC-LBL magnetic detector with the
- lead-glass counter system.3718. An end view of the SLAC-LBL magnetic detector with the lead-
- glass counter system. The two proportional chambers around the beam pipe and the trigger counters are not shown. 38
- 19. The fractional containment of showers for 1, 2, 5, 10, and
  20 GeV incident electrons vs. (a) counter length and (b)
  counter radius. (Ref. 27)

xi

xii

Page

48

50

51

53

54

26.

- A schematic diagram of the LED monitoring system for the lead-glass counters.
- 21. The distribution of the measured energy in the lead-glass counter system divided by the colliding beam energy for electrons from Bhabha scattering between 3.2 and 3.7 GeV. The resolution is  $\sigma/E = 4.8\%$ .
- 22. The distribution of the measured energy in the lead-glass counter system divided by the colliding beam energy for electrons from Bhabha scattering at 1.89 GeV. The resolution is  $\sigma/E = 6.7\%$ .
- 23. The energy resolution as a function of energy for electrons in the lead-glass counter system, as determined from Bhabha scattering events. The curve is at  $\sigma/E = 9Z/\sqrt{E}$ , the resolution obtained in a test beam with a subset of the leadglass counter system. In both cases there was 1 X<sub>0</sub> of aluminum in front of the lead-glass.
- 24. The distribution of the difference between the measured position in the lead-glass counter system and the projected track position in the horizontal coordinate in the back blocks for electrons from Bhabha scattering between 3.2 and 3.7 GeV. The resolution is 3 cm.
- 25. The scatter plots of  $E_{AC}^{AC}/p$  vs.  $E_{tot}^{AC}/p$  for (a)  $e^+e^- \rightarrow e^+e^$ in the  $E_{cm}^{Cm}$  range of 6.4 to 7.4 GeV, (b)  $e^+e^- \rightarrow \mu^+\mu^-$  in the  $E_{cm}^{Cm}$  range of 6.4 to 7.4 GeV, (c)  $e^+e^- \rightarrow \mu^+\mu^-$  in the  $E_{cm}^{Cm}$  range of 6.4 to 7.4 GeV and (d)  $e^+e^- \rightarrow \psi \rightarrow$  hadrons at

 $E_{cm} = 3.098$  GeV.  $E_{AC}$  is the energy deposited in the active converters.  $E_{tot}$  is the total energy deposited in the leadglass counter system. p is the momentum of the particle. The observed and true (unfolded) charged multiplicity dis-

- tributions for D decays. (Ref. 29)
- 27. The observed total charged multiplicity distributions for multiprong electron data (open dot) and Monte Carlo calculations (closed dot) with three or more prongs in four E<sub>cm</sub> regions. Both sets of points are normalized to one for comparison.
- 28. The observed production cross sections for eµ events,  $\sigma_{e\mu}$ , and for eh events,  $\sigma_{eh}$ , vs.  $E_{cm}$  (a) before and (b) after charm background subtraction. The vertical lines are statistical errors and the horizontal lines show the  $E_{cm}$  range covered by each point. The curves are the theoretical predictions including triggering efficiencies, geometric acceptances and kinematic cuts for a heavy lepton  $\tau$  with  $m_{\tau} = 1.80$ , 1.85, and 1.90 GeV/c<sup>2</sup>.
- 29. The r distributions (eq. 16) for the electrons of the anomalous eµ and eh events, the muons of the anomalous eµ events and the hadrons of the anomalous eh events (a) before and (b) after charm background subtraction. The curves are the theoretical predictions including triggering efficiencies, geometric acceptances and kinematic cuts for a heavy lepton

xiv

Page

58

79

81

 $\tau$  with  $m_{\tau} = 1.85 \text{ GeV/c}^2$ ,  $m_{v_{\tau}} = 0$  and V-A coupling. In these plots, the four  $E_{cm}$  regions have been combined. The hadron curve has been calculated with the assumptions explained in the text.

97

Page

- 30. The  $\theta_{copl}$  distribution (eq. 34) for all the anomalous twoprong ex events before charm background subtraction. The curve is the theoretical prediction including triggering efficiencies, geometric acceptances and kinematic cuts for a heavy lepton  $\tau$  with  $m_{\tau} = 1.85 \text{ GeV/c}^2$ ,  $m_{V_{\tau}} = 0$  and V-A coupling. In this plot, the four  $E_{cm}$  regions have been combined.
- 31. The distributions of the shower pulse heights  $H_c$  for Bhabba scattering events in the  $\psi(3095)$  data excluding 10% of the counter width at each azimuthal edge and for the full counter length. Data from all 21 shower counters have been folded together. Part (a) shows the fall cycle data and part (b) shows the spring cycle data.
- 32. The shower counter cosmic ray efficiency vs. the longitudinal position Z on the counter for the full counter width. Data from all 21 shower counters and 6 scintillation counters have been folded together. Part (a) shows the fall cycle data and part (b) shows the spring cycle data.
- 33. The shower counter cosmic ray efficiency vs. the longitudinal position Z on the counter excluding 5% of the counter width at each azimuthal edge. Data from all 21 shower

counters and 6 scintillation counters have been folded together. Part (a) shows the fall cycle data and part (b) shows the spring cycle data.

34. The shower counter cosmic ray efficiency vs. the azimuthal position  $f_{\phi}$  on the counter for the full counter length. Data from all 21 shower counters and 6 scintillation counters have been folded together. Part (a) shows the fall cycle data and part (b) shows the spring cycle data.

99

102

105

Page

106

107

xv

xvi

### I. INTRODUCTION

1

In the past few years, substantial evidence has been found  $^{1-14}$  for the existence of a new charged particle in electron-positron annihilation. When the evidence for this new particle was first found in the form of electron-muon events by the SLAC-LBL Magnetic Detector Collaboration, it was called the U as a temporary name because its nature was unknown. Since that time, more information has become available on the nature of the new particle. There is now substantial evidence that it is a lepton. The name  $\tau$  has been given to it because it is the third charged lepton to be found. ( $\tau$  comes from  $\tau p_1 \tau \sigma v$ , the Greek word for third.)

This dissertation studies anomalous electron-muon and electron-hadron production in events with two detected charged particles (two-prong events) from electron-positron annihilation. Anomalous events are events which are not subject to conventional explanations; examples of conventional explanations are misidentification of particles or the decay of ordinary or strange hadrons.

The purposes of this dissertation are:

 to confirm previous observations<sup>1-14</sup> of anomalous two-prong electron-muon (eµ) events using a lead-glass counter system with good electron identification,

to report for the first time anomalous two-prong electron-hadron
 (eh) events with any number of detected photons,

 to show that charm production contributes only a minority of the anomalous two-prong signal,

4) to show that the majority of the anomalous two-prong signal is

consistent with heavy lepton production,

5) to present branching ratios, excitation functions, momentum and coplanarity distributions pertaining to the anomalous two-prong signal.

### 11. THEORY

3

Since the new lepton is experimentally found to decay predominantly or completely through weak interactions, only those theories in which the electromagnetic decay modes are forbidden or strongly suppressed are considered.

# A. Sequential Heavy Leptons<sup>15</sup>

A sequential heavy lepton  $\tau$  has its own unique and completely conserved lepton number and associated neutrino. It is part of a sequence:

$$\begin{array}{cccc} e^{\pm} & \nu_{e}, \overline{\nu}_{e} \\ \mu^{\pm} & \nu_{\mu}, \overline{\nu}_{\mu} \\ \tau^{\pm} & \nu_{\tau}, \overline{\nu}_{\tau} \\ \end{array}$$
(1)

which may or may not be finite in number.

Since all lepton numbers are separately conserved, the reactions

$$\tau^{\pm} + e^{\pm} + \gamma, \quad \tau^{\pm} + \mu^{\pm} + \gamma \tag{2}$$

cannot occur. Therefore the t can only decay through weak interactions. The leptonic decay modes for a sequential heavy lepton are

$$\tau^{+} \rightarrow \overline{v}_{\tau} + e^{+} + v_{e}$$

$$\tau^{-} \rightarrow v_{\tau} + e^{-} + \overline{v}_{e}$$

$$\tau^{+} \rightarrow \overline{v}_{\tau} + \mu^{+} + v_{\mu}$$

$$\tau^{-} \rightarrow v_{\tau} + \mu^{-} + \overline{v}_{\mu}$$
(3)

and for a t with a sufficiently large mass, the hadronic decay modes

are

$$\tau^+ \rightarrow \overline{\nu}_{\tau}$$
 + hadrons (4)  
 $\tau^- \rightarrow \nu_{\tau}$  + hadrons

For a sequential heavy lepton with conventional weak interactions,

$$\Gamma(\tau^- + \nu_{\tau} e^- \overline{\nu}_{e}) = \Gamma(\tau^- + \nu_{\tau} \mu^- \overline{\nu}_{\mu})$$
 (5)

where  $\Gamma$  is the width of the indicated decay mode.

Table I gives the expected branching ratios for a sequential heavy lepton with a mass of 1.8 GeV/c<sup>2</sup> using conventional weak interaction theory as worked out by Thacker and Sakurai, and by Tsai.

4

# B. Paraleptons<sup>17,18</sup>

An electron associated paralepton E, as defined by Liewellyn Smith,<sup>17</sup> has the lepton number of the oppositely charged e. Therefore, it cannot decay electromagnetically. It can only decay weakly. The leptonic decay modes for an electron associated paralepton are

$$E^{+} + v_{e} + e^{+} + v_{e}$$

$$E^{-} + \overline{v}_{e} + e^{-} + \overline{v}_{e}$$

$$E^{+} + v_{e} + \mu^{+} + v_{\mu}$$

$$E^{-} + \overline{v}_{e} + \mu^{-} + \overline{v}_{\mu}$$
(6)

and the hadronic decay modes are

$$E^{+} + v_{e}^{+} + hadrons$$

$$E^{-} + \overline{v_{e}}^{+} + hadrons$$
(7)

For an electron associated paralepton with V-A coupling and all left-handed neutrinos.

$$\Gamma(E^- \to \overline{\nu}_e \ e^- \ \overline{\nu}_e) \ * \ 2\Gamma(E^- \to \overline{\nu}_e \ \mu^- \ \overline{\nu}_\mu)$$
(8)

where  $\Gamma$  is the width of the indicated decay mode.

Recent results<sup>19</sup> on anomalous ee and uu events have indicated that the branching ratio for the heavy lepton to decay into e is equal to the branching ratio for the heavy lepton to decay into  $\mu$ . These results have ruled out the possibility that the heavy lepton is an electron associated paralepton.

### TABLE I

The predicted branching ratios for a  $\tau^-$  sequential charged heavy lepton with a mass of 1.8 GeV/c<sup>2</sup>, an associated neutrino mass of 0.0, and V-A coupling. The predictions are based on Ref. 16.

		Number of
		charged particles
Decay mode	Branching ratio	in final states
ν <sub>τ</sub> e v <sub>e</sub>	0.16	1
៴ <sub>τ</sub> μ៑ν <sub>μ</sub>	0.16	1
ν <sub>τ</sub> π	0.10	1
ν <sub>τ</sub> K	0.01	1
ν <sub>τ</sub> ρ <sup>-</sup>	0.23	1
ν <sub>τ</sub> κ*-	0.02	1
ν <sub>τ</sub> Α <sub>1</sub>	0.09	1,3
v_ (hadron continuum)	0.23	1, 3, 5

A muon associated paralepton M can also be similarly defined. However the lower limit on its mass set by muon neutrino experiments<sup>20</sup> eliminates it from consideration here.

# C. Ortholeptons<sup>17</sup>

An electron associated ortholepton e<sup>\*</sup> has the same lepton number as the same charge e. It is also called an excited electron. Ordinarily the dominant decay mode for an electron associated ortholepton would be electromagnetic

$$e^{\star\pm} \rightarrow e^{\pm} + \gamma \tag{9}$$

However, as discussed by Low,<sup>21</sup> the coupling at the  $e^+e\gamma$  vertex is of the form

$$\left(\frac{e}{M}\right) \overline{\psi}_{e}^{* \sigma}{}_{\mu\nu} \psi_{e} f^{\mu\nu}$$
(10)

where M is an arbitrary mass. By making M very large, the electromagnetic decay can be suppressed and the weak decays can dominate. The leptonic decay modes for an electron associated ortholepton are

$$e^{\star +} + \overline{v}_{e} + e^{+} + v_{e}$$

$$e^{\star -} + v_{e} + e^{-} + \overline{v}_{e}$$

$$e^{\star +} + \overline{v}_{e} + \mu^{+} + v_{\mu}$$

$$e^{\star -} + v_{e} + \mu^{-} + \overline{v}_{\mu}$$
(11)

and the hadronic decay modes are

$$e^{*+} + \overline{v}_e + hadrons$$
 (12)  
 $e^{*-} + v_e + hadrons$ 

For an electron associated ortholepton with conventional weak

interactions,

$$\Gamma(e^{*-} + v_e e^{-} \overline{v_e}) = \Gamma(e^{*-} + v_e \mu^{-} \overline{v_e})$$
(13)

where  $\Gamma$  is the width of the indicated decay mode.

A muon associated ortholepton  $\mu^*$  can also be similarly defined. However the lower limit on its mass set by muon neutrino experiments<sup>20</sup> eliminates it from consideration here.

7

Therefore the only likely candidates are the sequential heavy lepton  $\tau$  and the excited electron  $e^*$ . The sequential heavy lepton  $\tau$ is used here as a model for our data. However our data cannot distinguish between a sequential heavy lepton and an excited electron.

## 111. SUMMARY OF PREVIOUS RESULTS

There are three strong signatures for the production of the heavy lepton  $\tau$ . One signature is

$$e^+ + e^- + e^{\pm} + \mu^{\mp} + no$$
 other particles detected (14)

produced through

Table II lists the  $e\mu$  data previously reported. Figs. 1-6 show the lepton momentum spectra and the production cross sections.

Figures 1 and 2 show the r distributions for  $e\mu$  events from the SLAC-LBL Magnetic Detector Collaboration<sup>3</sup> in four E regions. The parameter r is defined as

$$r = (p - p_0)/(p_{max} - p_0)$$
 (16)

where p is the momentum of the particle in GeV/c and  $p_0$  is the lower momentum cutoff and  $p_{max}$  is the maximum momentum allowed for the heavy lepton hypothesis. The range of r is  $0 \le r \le 1$ .

Figure 3 shows the  $\cos \theta_{coll}$  distributions for eµ events from the SLAC-LBL Magnetic Detector Collaboration<sup>3</sup> in three  $E_{cm}$  regions. The parameter  $\cos \theta_{coll}$  is defined as

$$\cos \theta_{\text{coll}} = -(\vec{p}_1 \cdot \vec{p}_2)/(|\vec{p}_1| |\vec{p}_2|)$$
(17)

where  $\vec{p}_1$  and  $\vec{p}_2$  are the momenta of particle 1 and particle 2 respectively.

A second signature for the production of a heavy lepton pair is

$$e^{+} + e^{-} + \mu^{\pm} + x^{\mp} + \geq 0 \text{ photons}$$
(18)

produced through

on.	identificati				5.2	
	Good hadron				ť	
Ë.	Good Y detec	0.7	11	0,15	4.0	DASP Group
₽	against char				5.0	
ent	Strong argum			1.0	G	Group
	Very clean.	1.9	23	0.3	3.6	PLUTO
	coupling.					
н	m <sub>τ</sub> , m <sub>VT</sub> , τ-ν	-			7.8	detector
radi	Used to dete			0.65	ť	magnetic
ce.	First eviden	46	190	0.65	3.8	SLAC-LBL
		events	events	(GeV/c)	(GeV)	detector
		ground	of eu	on Pe	range	group or
	Comment	of back-	number	limits		Experimental
		Number	Total	Lower		

The data on  $e^{\pm} \mu^{\mp}$  events. See references for further details.





Fig. 1. The r distribution for eu events from the SLAC-LBL Magnetic Detector Collaboration in the  $E_{\rm CM}$  region of 3.8 to 7.8 GeV. The distribution has been corrected for background. The solid curve is for the 3-body, leptonic decay of the t with the indicated parameters. The dash and dash-dot curves are for the 2-body leptonic decay modes of a boson; the former is for no spin alignment of the boson, and the latter is for a spin 1 boson produced only in the helicity = 0 state. (Refs. 1, 3, 14)



 $\theta_{\rm coll}$ 





Fig. 2. The r distributions for eu events from the SLAC-LBL Magnetic Detector Collaboration in three  $E_{Cm}$  regions. The distributions have been corrected for background. See the caption to Fig. 1. (Refs. 1, 3, 14)

-

Fig. 3. The cos  $\theta_{coll}$  distributions for eu events from the SLAC-LBL Magnetic Detector Collaboration in three  $E_{cm}$  regions. The distributions have been corrected for background. The solid curve is for  $m_{\tau} = 1.9 \ {\rm GeV/c^2}$ ,  $m_{V_{\tau}} = 0.0$  and V-A coupling. (Refs. 1, 3, 14)



Fig. 4. The observed eµ production cross section  $\sigma_{eµ}$  vs.  $E_{cm}$  for eµ events from the SLAC-LBL Magnetic Detector Collaboration. The vertical lines are statistical errors. The horizontal lines show the  $E_{cm}$ range covered by each point. No events <u>before</u> background subtraction were found in the  $E_{cm}$  range of 3.0 to 3.6 GeV. We show the 90% confidence upper limit on  $\sigma_{eµ}$  if 2.3 events had been found. The curves are for  $m_T = 1.8$  or 2.0 GeV/c<sup>2</sup>. The product  $B_e B_\mu$  is adjusted for each mass choice to give the best fit. The  $\chi^2$  probability of these fits is 90%. (Refs. 1, 3, 14)





14

Fig. 5. The electron momentum distribution for eµ events from the PLUTO Group in the  $E_{\rm CM}$  region of 4.0 to 5.0 GeV. The distribution has been corrected for trigger and detector acceptance, hadron punchthrough and electron detection efficiency. The solid curve is calculated for V-A coupling,  $m_{\rm T}$  = 1.91 GeV/c<sup>2</sup> and  $m_{V_{\rm T}}$ 0. Note that the detection efficiency distorts the lower part of the spectrum. (Refs. 8, 10, 13)





2-78

Fig. 6. The muon production cross section vs.  $E_{cm}$  for (a) inclusive twoprong ux events, (b) inclusive multiprong muon events and (c) exclusive µe events from the PLUTO Group. The cross sections are given for muon momenta greater than 1 Gev/c. They have been corrected for trigger and detector acceptance, and for hadron punchthrough. Part (a) has also been corrected for backgrounds from quantum electrodynamic processes. Part (c) has also been corrected for lectron detection efficiency. The solid curves are calculated for V-A coupling,  $m_{\tau} = 1.91 \text{ GeV/c}^2$  and  $m_{v_{\tau}} = 0$ . (Refs. 8, 10, 13)

x" + neutral particles

where x is a charged lepton or hadron. Table III lists the µx data previously reported. Figures 7-8 show the lepton momentum spectra.

A third signature for the production of a heavy lepton pair is

$$e^+ + e^- + e^{\pm} + x^{\mp} + \ge 0$$
 photons (20)

produced through

e

 $e^+ + e^- \rightarrow \tau^+$ 

$$+ e^{-} + \tau^{+} + \tau^{-}$$
(21)
$$= \sqrt{\frac{1}{\nu_{\tau}}} e^{+} v_{e} + \sqrt{\frac{1}{\nu_{\tau}}} x^{-} + neutral particles$$

where x is a charged lepton or hadron. Table IV lists the ex data previously reported. Figures 9-12 show the lepton momentum spectra and the production cross sections.

Figure 12 shows the electron production cross section ratio r, for two-prong ex events from the DELCO Group  $5 \text{ vs. E}_{cm}$ . The parameter r is defined as

$$\mathbf{r}_{\mathbf{e}} = \sigma(\mathbf{e}^{\dagger}\mathbf{e}^{-} \rightarrow \mathbf{e}\mathbf{x} + \geq 0 \ \gamma' \mathbf{s}) / \sigma(\mathbf{e}^{\dagger}\mathbf{e}^{-} \rightarrow \mu^{\dagger}\mu^{-})$$
(22)

where o is the cross section of the indicated process.

Next we present a summary of the properties of the heavy lepton  $\tau$ :

#### 1) τ Mass

Table V gives the  $m_{\tau}$  values previously reported. Figure 13 shows the  $\mathbf{p}_i$  distribution for  $e\mu$  events from the SLAC-LBL Magnetic Detector Collaboration<sup>1</sup> with  $E_{cm} > 4.8$  GeV. The parameter p is defined as

$$\mathbf{p}_{1} = |\vec{\mathbf{p}}_{1} \times \vec{\mathbf{p}}_{2}| / |\vec{\mathbf{p}}_{1} - \vec{\mathbf{p}}_{2}|$$
(23)

Maryland- Princeton- Pavia	DASP Group	PLUTO Group	SLAC-LBL magnetic detector	Maryland- Prínceton- Pavia	Experimental group or detector
7	4.0 to 5.2	4.0 to 5.0	4.0 to 7.8	4.8	Ec.m. range (GeV)
1.15 ~0.1	0.7 ~0.1	0.7 ~0.1	1.0 0.2	1.0 ~0,1	Lower Limits on <sup>Pµ</sup> Px (GeV/c)
8+4 ~3	≈12	~230	103 ± 18 above Ec.m. = 5.8 GeV	9.1	Number of µx events above background
Good charged prong detection.	Can be directly compared to ex events.	Strong signal in 3 E <sub>C.m.</sub> ranges in 45 GeV regions.	Strong signal above 5.8 GeV. Clearly different from µ+>2 charged particle events.	First evidence. Small statistics.	Comments
7	12	01,6	2	4	Ref.





Fig. 7. The muon momentum distributions for (a) two-prong  $\mu x$  events and (b) multiprong muon events from the SLAC-LBL Magnetic Detector Collaboration in the E<sub>cm</sub> region of 5.8 to 7.8 GeV. The solid curve represents the expected cross section for a heavy lepton with a V-A decay, a branching fraction to  $\mu\nu\nu\nu$  of 0.17, and a mass between 1.6 and 2.0 GeV/c<sup>2</sup>. (Refs. 2, 3, 14)

TABLE	
V	

The data on  $e^{\pm}x^{\mp}$  events. See references for further details.

	15	J.		
Determ		•	3.684	DASP Group
large			7.4	
e sel	229	ů	to	
Very,		ٽ	3.684	DELCO Group
eventi				
charge				
0.24±				
±0.06	<u></u>			
К/п т		-	5.2	
modes	60	•2	to	
See h		•2	4.0	DASP Group
	background	(GeV/c)	(GeV)	detector
	above	on Pe	range	group or
<u>0</u>	ex events	limits	с. В.	Experimental
	Number of	Lower		



Fig. 8. The muon momentum distributions for two-prong  $\mu x$  events from the PLUTO Group in three  $E_{\rm CM}$  regions. The cross sections have been corrected for trigger and detector acceptance, hadron punchthrough and backgrounds from quantum electrodymanic processes. The fits assume V-A coupling,  $m_{\tau} = 1.91 \ {\rm GeV/c^2}$  and  $m_{\nu_{\tau}} = 0$ . (Refs. 9, 10, 13)



Fig. 9. The electron momentum distribution for two-prong ex events from the DASP Group in the  $E_{\rm Cm}$  region of 4.0 to 5.2 GeV. The fit assumes V-A coupling,  $m_{\tau} = 1.90 \ {\rm GeV/c^2}$  and  $m_{v_{\tau}} = 0$ . (Refs. 11, 12, 13) 22



Fig. 10. The electron production cross section vs.  $E_{\rm cm}$  for two-prong exevents from the DASP Group.  $A_{\rm ex}$  is the acceptance of the apparatus for ex events. The fit assumes V-A coupling,  $m_{\tau} = 1.80$  GeV/c<sup>2</sup> and  $m_{v_{\tau}} = 0$ . (Refs. 11, 12, 13)

21



Fig. 11. The electron momentum distribution for two-prong ex events from the DELCO Group in the  $E_{\rm CM}$  region of 3.8 to 5.0 GeV. The curve is a theoretical Monte Carlo calculation for the 3-body leptonic decay of a mass 1.85 GeV/c<sup>2</sup>  $\tau$ . (Ref. 5)

MOMENTUM

(MeV/c) 328383

ELECTRON

9-77



Fig. 12. The electron production cross section ratio  $r_e$  (eq. 22) vs.  $E_{cm}$  for two-prong ex events from the DELCO Group. The curve shows the expected smooth yield from a heavy lepton pair with a branching ratio of 0.15 to  $v_{\tau} e^{-} \bar{v}_e$ . (Ref. 5)

23

## TABLE V

					<u> </u>
	Data		τ Mass		
Experiment	Used	Method	(GeV/c <sup>2</sup> )	Comment	Ref.
		₽⊥	1.91 ± .05	Statistical error	
SLAC-LBL		cos <sup>0</sup> coll	1.85 ± .10	Statistical error	1.3
magnetic	LAC-LBL agnetic etector LUTO Group $\mu x$ $e_{\mu}$ $p_{\perp}$ 1.91 ± .05 Statistical error 1.85 ± .10 Statistical error 1.88 ± .06 Statistical error 1.90 ± .10 Statistical and systematic error 1.93 ± .05	-, -			
Gelector		composite	Indu(def, $0^{-1}$ )Statistical error11.91 ± .05Statistical error $\theta_{coll}$ 1.85 ± .10Statistical errorr1.88 ± .06Statistical errorpsite1.90 ± .10Statistical and systematic error $\mu x$ 1.93 ± .0510ex1.807 ± .02011		
PLUTO Group	μж	σμχ	1.93 ± .05		10
DASP Group	ex	or ex	1.807 ± .020		11
DELCO Group	ex	ďex	1.82 ± .02	Rough estimate	5





Fig. 13. The p<sub>1</sub> distribution for eµ events from the SLAC-LBL Magnetic Detector Collaboration with  $E_{CR} > 4.8$  GeV. The distribution has been corrected for contamination by background events. The solid line is a theoretical calculation of this distribution for a lepton with  $m_{\tau} = 1.90$  GeV/c<sup>2</sup>,  $m_{\nu_{\tau}} = 0.0$  and V-A coupling. (Refs. 1, 3, 14)

where  $\vec{p}_1$  and  $\vec{p}_2$  are the momenta of particle 1 and particle 2 respectively.

# 2) $v_{\tau}$ Mass

Figure 14 shows the r distribution for all eµ events from the SLAC-LBL Magnetic Detector Collaboration.<sup>1</sup> The solid curves are for  $m_{\tau} = 1.90 \text{ GeV/c}^2$ , V-A coupling and  $m_{v_{\tau}} = 0.0$ , 0.5 and 1.0 GeV/c<sup>2</sup> respectively. As  $m_{v_{\tau}}$  increases, the quality of the fit decreases. The 95% confidence upper limit on  $m_{v_{\tau}}$  is

$$m_{v_{\tau}} \leq 0.60 \text{ GeV/c}^2$$
 (24)

Using  $\mu x$  events, the PLUTO Group  $^{10}$  has found that the 90% confidence upper limit on  $m_{_{\rm U}}$  is

$$\mathbf{m}_{\mathbf{v}_{\tau}} \leq 0.54 \ \mathrm{GeV/c}^2 \tag{25}$$

### 3) $\tau - v_{\tau}$ Coupling

The dash curve in Fig. 14 is for V+A coupling,  $m_{\tau} = 1.90 \text{ GeV/c}^2$ and  $m_{v_{\tau}} = 0.0$ . From Fig. 14, the SLAC-LBL Magnetic Detector Collaboration<sup>1</sup> has found that V+A coupling has a  $\chi^2$  probability of less than 0.1% to fit the r distribution and V-A coupling has a  $\chi^2$  probability of 60%. If the r = 0.1 point is ignored, the  $\chi^2$  probability for V+A coupling is 5%. An additional argument against V+A coupling is presented in Table VI. It shows that one cannot obtain a consistent

 $m_{\tau}$  value assuming V+A coupling.

Using  $\mu x$  events, the PLUTO Group<sup>10</sup> has found that V-A coupling is slightly favored over V+A coupling.

### 4) Branching Ratios

Table VII gives the existing data on the purely leptonic decay modes of the  $\tau$ . B<sub>e</sub> is the branching ratio for  $\tau^- \rightarrow \nu_{\tau} e^- \overline{\nu_e}$  and B<sub>µ</sub>



Fig. 14. The r distribution for all eP events from the SLAC-LBL Magnetic Detector Collaboration. The distribution has been corrected for background. The solid curves are for  $m_{\tau} = 1.90 \text{ GeV/c}^2$ , V-A coupling, and  $m_{\nu_{\tau}}$  in GeV/c<sup>2</sup> as indicated. The dashed curve is for V + A coupling,  $m_{\tau} = 1.90 \text{ GeV/c}^2$  and  $m_{\nu_{\tau}} = 0.0$ . (Refs. 1, 3, 14)

# TABLE VI

The measurements of  $m_{\tau}$  using eµ data from the SLAC-LBL Magnetic Detector Collaboration and assuming V+A coupling and  $m_{V_{\tau}} = 0.0$ . (Refs. 1, 3)

Method	P <sub>1</sub>	cos <sup>θ</sup> coll	r
			Upper limit is
Mass (GeV/c <sup>2</sup> )	2.12 ± .05	1.95 ± .10	1.76 with 95%
			CL.

30

# TABLE VII

The purely leptonic decay modes of the  $\tau$ .  $B_e$  is the branching ratio for  $\tau^- + v_{\tau}e^- \vec{v}_e$  and  $B_{\mu}$  is the branching ratio for  $\tau^- + v_{\tau}\mu^- \vec{v}_{\mu}$ . The acceptances were calculated assuming V-A coupling,  $m_{\tau} = 1.9 \text{ GeV/c}^2$  and  $m_{v_{\tau}} = 0.0$ .

Experimental				
group or	Data			
detector	Used	вогв	Comment	Ref.
SLAC-LBL magnetic detector	cμ	0.186±.010±.028	Assume $B_e = B_\mu$ . First error is statistical, second is systematic.	1
SLAC-LBL magnetic detector	μх	0.175±.027±.030	Assume B <sub>x</sub> = 0.85. First error is statistical, second is systematic.	1
PLUTO Group	μж	$B_{\mu} = 0.14 \pm .034$		10
PLUTO Group	µ <b>х,е</b> µ	$B_e = 0.16 \pm .06$		10
DASP Group	eμ	0.182±0.028	Assume $B_e = B_{\mu}$ .	11
DELCO Group	ex	0.15 <sup>+.01</sup> 03		5
Iron Ball	μμ	0.22+.07 08		7
Maryland- Princeton- Pavia	μх	0.20 <sup>+.10</sup> 08		7

is the branching ratio for  $\tau \rightarrow v_{\tau} \mu \overline{v_{\mu}}$ . Table VIII gives the existing data on the semileptonic decay modes of the  $\tau$ . Table IX gives the upper limits on the rare decay modes of the  $\tau$ . The acceptances were calculated assuming V-A coupling,  $m_{\tau} = 1.9 \text{ GeV/c}^2$  and  $m_{v_{\tau}} = 0.0$ .

# 5) Total e<sup>+</sup>e<sup>-</sup> Annihilation Cross Section

In Fig. 15, the PLUTO Group<sup>22</sup> has shown that the directly measured total cross section for two-prong events is large enough to easily contain the two-prong events from  $\tau^+\tau^-$  production, assuming relative decay rates similar to those in Table I. R<sub>2pr</sub> is defined as

$$R_{2pr} = \sigma_{2pr} / \sigma_{\mu\mu}$$
(26)

where  $\sigma_{2pr}$  is the total cross section for two-prong events and  $\sigma_{\mu\mu}$  is the  $\mu$  pair production cross section.

TABLE VIII

The semileptonic decay modes of the  $\tau$ . The acceptances were calculated assuming V-A coupling,  $m_{\tau} = 1.9 \text{ GeV/c}^2$  and  $m_{v_{\tau}} = 0.0$ .

Experimental group or detector	Decay mode (for $\tau$ )	Branching ratio	Ref.
DASP Group	ρ + ν <sub>τ</sub>	0.24 ± .09	12
DASP Group	$\pi^{-} + \nu_{\tau}$	$\mathbf{B}_{\mathbf{e}} \mathbf{B}_{\pi} \Rightarrow 0.004 \pm .005$	12
PLUTO Group	$"A_{1}"^{-} + v_{\tau}$	0.11±.04±.03	10
		for "A <sub>1</sub> " $\rightarrow$ all	10

## TABLE IX

The upper limits on the rare decay modes of the  $\tau$ . The acceptances were calculated assuming V-A coupling,  $m_{\tau} = 1.9 \text{ GeV/c}^2$  and  $m_{\nu_{\tau}} = 0.0$ .

Experimental		Upper limit		
group or		dna matia	C T	Ref
detector	Mode	Ing Tatto	0.1.	
PLUTO Group	$\tau \rightarrow$ (3 charged particles)	0.01	95%	3
PLUTO Group	$\tau^{-}$ $\Rightarrow$ (3 charged leptons)	0,01	95%	3
SLAC-LBL mag- netic detector	$\tau^- \rightarrow (3 \text{ charged leptons})^-$	0.006	90%	3
SLAC-LBL mag- netic detector	$\tau^- \rightarrow \rho^- + \pi^0$	0.024	90%	3
PLUTO Group	$\tau^{-} \neq e^{-} + \gamma$ $\tau^{-} \neq \mu^{-} + \gamma$	0.12	90%	3



Fig. 15. The ratio  $R_{2pr}$  (eq. 26) vs.  $E_{cm}$  for  $e^+e^- + 2$  prong events with radiative corrections from the PLUTO Group. The curve indicates the contribution to  $R_{2pr}$  from a heavy lepton with a mass of 2.0 GeV/c<sup>2</sup>. The different symbols represent data taken at different times. (Ref. 22)

#### IV. APPARATUS

35

A. <u>SPEAR</u><sup>19,23,24,25</sup>

In the SPEAR  $e^+e^-$  Colliding Beams Facility (Fig. 16), a single bunch of electrons and a single bunch of positrons of equal energy move in a common vacuum chamber and magnetic guide field. The circulation frequency is 1.28 MHz. The bunches collide with zero crossing angle at each of the two interaction regions, the east pit and the west pit. The total energy of the interaction,  $E_{cm}$ , is twice the energy of the beam,  $E_b$ . SPEAR operates in the energy range of  $2 \lesssim E_{cm} \lesssim 8$  GeV. The error in calibration of the energy of the ring is estimated to be ±0.1% and the error in setting the energy is ±0.1 MeV.

Electron-positron interactions occur at a rate proportional to the cross section for the process. The proportionality factor, called the luminosity, depends on a number of factors including the current and cross-sectional area of each beam. The instantaneous luminosity at SPEAR at the beginning of a fill is approximately  $(E_b/1.8)^4 \ 10^{30}$  $\rm cm^{-2}\ sec^{-1}$  for  $E_b \lesssim 3\ GeV$  and  $10^{31}\ \rm cm^{-2}\ sec^{-1}$  for  $E_b > 3\ GeV$ . The beam currents and luminosity decay exponentially in time. When the luminosity has dropped below optimum, the beams are dumped and the ring is refilled.

This experiment was carried out in the west pit interaction area of SPEAR using the SLAC-LBL magnetic detector with an additional leadglass electromagnetic shower detector system.

# B. The SLAC-LBL Magnetic Detector 19,23,24,25

The SLAC-LBL magnetic detector (Figs. 17 and 18) is a cylindrical array of counters and chambers used to track and identify particles.









Fig. 17. An exploded view of the SLAC-LBL magnetic detector with the lead-glass counter system.



Fig. 18. An end view of the SLAC-LBL magnetic detector with the leadglass counter system. The two proportional chambers around the beam pipe and the trigger counters are not shown.

38

 $\hat{\gamma}$ 

Starting from the interaction region and moving outward, the various components of the magnetic detector are:

- The beam pipe -- it has a mean radius of 8 cm and is made of 0.15 mm thick corrugated stainless steel. The average effective thickness, due to the corrugation, is 0.20 mm (approximately 0.011 radiation length).
- 2) The pipe counters -- there are four semi-cylindrical plastic scintillation counters forming two concentric cylinders at radii of 11 and 13 cm. Each cylinder is 0.69 cm thick and 36 cm long. They are part of the trigger and serve primarily to reduce triggers from cosmic rays. The efficiency of each counter for detecting minimum-ionizing particles is greater than 95%, as measured with cosmic rays.
- 3) The proportional chambers -- there are two cylindrical proportional chambers at radii of 17 and 22 cm with active regions in polar angle of 34°-146° and 29°-151°. Each of them consists of 512 sense wires parallel to the beam axis. The wire spacing in the inner chamber is 0.21 cm and the wire spacing in the outer chamber is 0.28 cm. They are each 0.0043 radiation length thick. The efficiency of each chamber for detecting prongs in multi-prong hadronic events is greater than 90%.
- 4) The cylindrical spark chambers -- there are four modules of concentric cylindrical magnetostrictive spark chambers at radii of 66, 91, 112, and 135 cm with active regions in polar angles of 31°-149°, 40°-140°, 43°-137°, and 45°-135°. Each module consists of two gaps and four "planes" with the wires at ±2° and ±4° with

respect to the beam axis. The wire spacing in each "plane" is 1.1 mm. Since the analysis requires sparks in three out of the four modules and two out of the four wires in each module, the efficiency of each wire "plane" is generally greater than 90%. The angular acceptance of the cylindrical spark chambers is approximately  $0.70 \ge 4\pi$  sr. The rms momentum resolution for a 1 GeV/c track is about 15 MeV/c. The structural support for the chambers consists of six, 6 mm wall, 5 cm diameter, aluminum posts at a radius of 79 cm, and a 1.3-cm thick aluminum cylinder at a radius of 1.49 m. These posts subtend about 6% of the solid angle. Since they can be major sources of multiple scattering, charged particles whose trajectories pass through one of them must be discarded, thereby reducing the effective angular acceptance of the detector.

- 5) The trigger counters -- there are forty-eight plastic scintillation counters immediately outside the aluminum cylinder supporting the spark chambers. Each counter is 2.5 cm thick, 23 cm wide, and 260 cm long. They are viewed from each end by a 5 cm diameter 56-DVP photomultiplier tube. These counters are part of the trigger (see Sec. IVD). They also provide time-of-flight information with a rms resolution of 0.35 nsec. This time-of-flight information allows a one-standard-deviation separation between  $\pi$  and K at 1.3 GeV/c momentum and a one-standard-deviation separation between K and p at 1.8 GeV/c momentum. The solid angle subtended by these counters is 0.65 x  $4\pi$  sr.
- 6) The solenoid -- an aluminum solenoidal coil 3.6 m long, 9 cm (approximately one radiation length) thick and 3.3 m in diameter

provides an axial magnetic field of approximately 4 kG which is uniform to 5% in the active region of the tracking chambers.

7) The shower counters -- there were twenty-four shower counters outside the solenoid. A counter consists of five 0.64 cm thick (approximately one radiation length) lead sheets each followed by a 0.64-cm sheet of Pilot F plastic scintillator. The counters are 48 cm wide and have active length of 3.1 m. They are viewed from each end by a 13 cm diameter RCA 4522 photomultiplier tube. These counters are part of the trigger (see Sec. IVD). However, their primary function is to discriminate between electrons and hadrons. They also have been used to a limited extent to detect photons. The plastic scintillators in the shower counters were inadvertently scratched during assembly of the counters. As a result, the attenuation length was reduced from 145 cm to typically 75 cm. The calibration of the shower counters is discussed in Appendix A and the efficiency of the shower counters is discussed in Appendix B.

Three shower counters in one octant of the magnetic detector have been removed and replaced by six scintillation counters. This was done to accommodate the lead-glass counter system and still preserve the original two-charged particle trigger of the magnetic detector (see Sec. IVD). The scintillation counters are arranged in such a way that every two of them replaces one of the shower counters. Each of the top two scintillation counters is 1.3 cm thick, 46 cm wide and 152 cm long and each of the bottom four scintillation counters is 1.9 cm thick, 46 cm wide and 152 cm long. They use exactly the same photomultiplier tubes, electronics and software as the three shower counters they replaced.

2

- 8) The iron flux return --- the detector is surrounded by iron which acts both as a flux return and a hadron filter. The iron is 20 cm thick around the circumference of the detector and 8 to 12 cm thick on the ends. One octant of the iron flux return has been removed and replaced by the lead-glass counter system.
- The muon spark chambers -- there are one or two large planar 9) magnetostrictive wire spark chambers outside the return iron in each octant to detect muons (level 1). The inner detector and the return iron are 1.7 interaction length thick, absorbing muons with momenta less than 350 MeV/c. There is a 15 to 20% probability that a hadron will be misidentified as a muon at level 1 due to decay or punchthrough. For better hadron rejection, five spark chambers and two 1.7 interaction length thick concrete absorbers are placed on top of the detector (levels 2 and 3). The solid angle subtended by the first concrete absorber is approximately 1.1 sr. The minimum average momentum required for a muon to pass through the first concrete absorber is 910 MeV/c. A spark chamber and a 1.7 interaction length thick iron absorber are placed behind the return iron in the octant opposite to the lead-glass counter system (level 2). The solid angle subtended by the iron absorber is approximately 0.6 sr. Figure 18 and Ref. 2 provide more details on this subject.
- 10) The luminosity monitors -- there are four counter telescopes, two at each end of the detector at ±20 milliradians from the beam line in the vertical plane, monitoring the luminosity of the storage

42

ring by observing small angle  $e^+e^-$  elastic scattering events. Large angle  $e^+e^-$  elastic scattering events in the main detector are also used to determine the luminosity.

# C. The Lead-Glass Counter System 26,27

A system of 318 lead-glass Cerenkov shower counters and three wire spark chambers has been added to one octant of the SLAC-LBL magnetic detector. This system covers a solid angle of approximately 6% of  $4\pi$  sr. The main purpose of this system is to provide good identification and energy measurement for electrons and photons produced in electronpositron annihilation.

High-energy electrons and photons incident on the lead glass form electromagnetic cascade showers. Upon entering the lead glass, highenergy electrons or photons ( $E_{e,\gamma} > 100$  MeV) start to lose energy through the emission of energetic photons or by pair production. The created particles then continue the process, thus producing still more particles. The resulting avalanche continues to build up until the typical energy of the photons has dropped to less than about 10 MeV. Below this energy, Compton scattering dominates over pair production. When the electrons (positrons) have less energy than the critical energy,  $E_{cr}$  (typical values are 8 MeV for Fb and 15 MeV for lead glass), ionization losses dominate over bremsstrahlung losses.

The characteristic distance within matter for an electron (positron) bremsstrahlung is approximately equal to the distance for pair production by a photon at high energies. This electromagnetic interaction length is referred to as the radiation length,  $X_0$ , and depends on the specific atomic properties (principally the atomic number and the density) of the shower medium. In the case of lead glass, the radiation length,  $X_{o}$ , is approximately 3 cm.

To the extent that ionization loss is independent of the particle's energy, the total charged particle path length, 2, will be proportional to the energy of the particle initiating the shower. In lead-glass counters, charged particles produce light via Cerenkov radiation. The total Cerenkov light output for shower particles with velocities near the speed of light is proportional to the charged particle path length. As the velocities of the shower particles decrease, the Cerenkov light output decreases. The charged particle path length adjusted for decreasing Cerenkov light output is

$$\tilde{\ell} = \ell \frac{(1 - \frac{1}{n^2 \beta^2})}{(1 - \frac{1}{n^2})}$$
(27)

where n is the refractive index of the lead glass and  $\beta c$  is the velocity of the shower particle. Only those shower particles with  $\beta > \frac{1}{n}$  radiate Cerenkov light in the lead glass.

In Fig. 19, the fraction of the shower contained vs.the length and the radius of the lead-glass counter is plotted. The average maximum path length for 1 GeV electrons is 50  $X_o$ . The average maximum path length for 5 GeV electrons is 250  $X_o$ . The average maximum path length for 20 GeV electrons is 1000  $X_o$ .

The lead-glass counters (Fig. 17) are in two layers, the active converters and the back blocks. The 52 active converters are each 90 cm tall, 10.8 cm wide and 10 cm thick (3.3  $X_0$ ). They are arranged in two horizontal rows of 26 counters each. Each active converter is viewed by a 3.5 in. diameter EMI 9531R photomultiplier tube. The



Fig. 19. The fractional containment of showers for 1, 2, 5, 10, and 20 GeV incident electrons vs. (a) counter length and (b) counter radius. (Ref. 27)

tubes are mounted vertically above the top row and below the bottom row.

46

The 266 back blocks are each 15 cm by 15 cm in cross section and 32.2 cm thick (10.5  $X_0$ ). They are arranged in a matrix of 14 horizontal rows and 19 vertical columns. Each back block is viewed by a 5 in. diameter EMI 9618R photomultiplier tube mounted horizontally on the back of the block.

There are two magnetostrictive wire spark chambers in front of the active converters, and a third chamber between the active converters and the back blocks.

The dynode signals from the phototubes are added together in horizontal rows. The signal from each row is amplified and fed into two latched discriminators with different thresholds for use in some modes of triggering the detector (see Sec. IVD). The anode signals, which have full widths of about 50 ns and peak currents of the order of 1 mA, are integrated and digitized by a 328-channel Large Scale Digitizer (LSD) developed and built at the Lawrence Berkeley Laboratory. The LSD provides ten-bit accuracy for a sufficient dynamic range. It was designed to reduce cost and complexity by sharing common timing and control signals among a large number of ADC channels.

In order to maintain good energy resolution and accuracy, it is necessary to monitor the gain of each of the counters as a function of time by measuring its response to a light source of known intensity. We used a single Monsanto MV5352 high-intensity light-emitting diode (LED) as a light source. The LED illuminates a bundle of low-attenuation plastic optical fiber cables (Dupont PFX-0715) which transmit the light to the 318 counters. This system provides each counter with a light pulse of about 100 ns in width. The integrated intensity of this light pulse is approximately equal to that from a 2-GeV electron or photon shower. The exact intensity varies from counter to counter.

In order to monitor fluctuations in the intensity of the LED itself, there are three reference scintillation counters which compare the light from the LED with the light from sources consisting of Americium-241 diffused in sodium-iodide crystals.

Figure 20 is a schematic diagram of the gain-monitoring system. With this system, the gains of the counters can be monitored to an accuracy of one to two percent over a period of nine months.

The LED monitoring system corrects for all fluctuations in the gains of the counters with time. It is still necessary, however, to determine an absolute calibration constant for each counter. The calibration constant relates the observed integrated pulse height to the amount of energy deposited in that counter by an electromagnetic shower. These calibration constants are determined by using electron-positron elastic scattering events (Bhabha scattering).

About 5000 Bhabha scattering events from the first three months of running with beam energy between 3.2 and 3.7 GeV were used for the calibration. Each event provides an equation of the form

$$\sum_{i} c_{i} A_{i} = E_{beam}$$
(28)

where the C's are the 318 unknown calibration constants, and the A's are the integrated pulse heights from the lead-glass counters after correction for gain variations with time as measured by the LED monitor-ing system, and  $E_{beam}$  is the colliding beam energy. The sum is taken over only those active converters and back blocks which are near the



48

Fig. 20. A schematic diagram of the LED monitoring system for the leadglass counters.

projected electron track as determined by the spark chambers of the magnetic detector. The calibration constants were found by a least square solution to the system of 5000 equations with 318 unknowns.

The energy resolution of the lead-glass counter system is limited by the presence of the 1  $X_0$  thick aluminum magnet coil in front of it. Energy losses in the coil degrade the resolution. In preliminary tests with a subset of the lead-glass counter system in an electron beam, the energy resolution of the lead-glass counters for electrons was found to be

$$\frac{\sigma}{E} = \frac{5\pi}{\sqrt{E}}$$
(29)

without the presence of the aluminum and

$$\frac{\sigma}{E} = \frac{9\%}{\sqrt{E}}$$
(30)

with 1  $X_0$  of aluminum in front of the lead glass. In both cases, E is the energy of the electrons in GeV. Subsequently, this resolution was reproduced with the entire lead-glass counter system under actual running conditions over a period of nine months.

Figure 21 shows the distribution of the measured energy in the lead-glass counter system divided by the colliding beam energy for electrons from Bhabha scattering used in the calibration. The average electron energy is 3.5 GeV. The resolution is about 4.8%. Figure 22 shows the same distribution for 1.89 GeV electrons. The resolution is about 6.7%. Both resolutions are in agreement with the  $9\%/\sqrt{E}$  expected from the test beam results. The data in Fig. 21 were taken in the first three months of running. The data in Fig. 22 were taken in the last two months of running. The fact that the energy resolution and accuracy are not measurably degraded demonstrates the stability of the



Fig. 21. The distribution of the measured energy in the lead-glass counter system divided by the colliding beam energy for electrons from Bhabha scattering between 3.2 and 3.7 GeV. The resolution is  $\sigma/E = 4.8\%$ .

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Fig. 22. The distribution of the measured energy in the lead-glass counter system divided by the colliding beam energy for electrons from Bhabha scattering at 1.89 GeV. The resolution is  $\sigma/E = 6.7\%$ .

system and the effectiveness of the LED monitoring system in tracking the counter gains. The resolution as a function of energy is shown in Fig. 23.

The position of a shower in the active converters and in the back blocks was measured by taking the centroid of the distribution of energy deposited. This provides two-dimensional information from the back blocks, but the active converters contribute useful information only in the horizontal coordinate since they are 90 cm tall. The position resolution was determined by comparing the position determined in this manner with the projected track position for electrons from Bhabha scattering. The distribution of this difference in the horizontal coordinate in the back blocks for electrons from 3.2 to 3.7 GeV is shown in Fig. 24. The resolution in this plot is 3 cm. This resolution does not vary significantly over the energy range of 1.5 to 3.7 GeV.

The spark chambers of the lead-glass counter system provide an additional measurement of the position of a shower. In the third spark chamber, which is behind a total of 4  $X_0$  of material, the position of a shower can be found with a resolution of about 2 cm in each of the two dimensions in the spark chamber plane by taking the centroid of the distribution of sparks. This resolution was determined using electrons from Bhabha scattering.

The position resolution for electrons in the first two spark chambers, which are behind only 1  $X_{o}$  of material, is about 1.5 cm.

There are three types of beam triggers used in this experiment. However, the data reported here are based on only the two-charged







Fig. 24. The distribution of the difference between the measured position in the lead-glass counter system and the projected track position in the horizontal coordinate in the back blocks for electrons from Bhabha scattering between 3.2 and 3.7 GeV. The resolution is 3 cm.

### particle trigger.

- Two-charged particle trigger -- this was the standard trigger for 1) the magnetic detector before the addition of the lead-glass counter system. The trigger rate of the magnetic detector is limited to a few triggers per second by the time required to recharge the spark chamber pulsing system. The rate of coincidences of two or more trigger counters with the solenoid on and 25 mA of stored current is approximately 3 KHz. Therefore, two or more shower counter latches are required in the trigger to suppress the lowenergy machine background and two or more pipe counter latches are required to suppress the cosmic ray background. The shower counter in the trigger is required to fire in coincidence with any one of the four adjacent trigger counters. A pickup upstream from the detector along one or the other beam detects the passage of the particle bunch and generates a master strobe. This master strobe is split and delayed to generate gates for the various counter latches. A coincidence between the beam pickup gate, two of the four pipe counter latches and two or more trigger-associated showers (TASH) forms the two-charged particle trigger. See Ref. 24 and Appendix B for shower counter latching efficiency.
- 2) One-charged particle and neutral trigger -- this is a new trigger introduced with the lead-glass counter system. It requires one charged particle in the magnetic detector and a minimum of about 70 MeV of energy deposited in the active converters or 150 MeV in the back blocks.
- 3) Total neutral trigger -- this is another new trigger introduced with the lead-glass counter system. It requires 100 MeV of energy in the active converters plus 1 GeV in the back blocks.

#### V. ANALYSIS

### A. Data Acquisition

The data were acquired during two periods of SPEAR operation. The first period, denoted as the fall cycle, began in October 1976 and ended in December 1976. The second period, denoted as the spring cycle, began in February 1977 and ended in June 1977. Table X presents the statistics pertaining to the data.

# B. Particle Identification in the Lead-Glass Counter System

Figure 25 shows the scatter plots of  $E_{AC}/p$  vs.  $E_{tot}/p$  where  $E_{AC}$  is the energy deposited in the active converters, and  $E_{tot}$  is the total energy deposited in the lead-glass counter system, and p is the momentum of the particle. We determined from these scatter plots cuts to be used in identifying electrons in the lead-glass counter system.

A particle detected in the lead-glass counter system is identified as an electron (e) by the following criteria:

- 1) The momentum of the particle, p, is greater than 0.40 GeV/c.
- 2) The energy deposited in the active converters,  $E_{\rm AC}$ , is greater than 150 MeV.
- 3) The total energy deposited in the lead-glass counter system divided by the momentum of the particle, E<sub>tot</sub>/p, is greater than 0.65. A particle detected in the lead-glass counter system is identified
- as a "no e" (muon or hadron) by the following criteria:
- 1) The momentum of the particle, p, is greater than 0.40 GeV/c.
- The particle is not identified as an electron by the lead~glass counter system.

# TABLE X

The average  $E_{c.m.}$ , the integrated luminosity and the number of twoprong events with one prong in the lead-glass counter system vs.  $E_{c.m.}$  range.

E <sub>c.m.</sub> range (GeV)	Average E c.m. (GeV)	Integrated luminosity (pb <sup>-1</sup> )	Number of two-prong events
3.7 - 4.0	3.78	2.3	16,600
4.0 - 4.4	4.16	2.5	13,500
4.4 - 6.4	4.96	3.7	15,700
6.4 - 7.4	6.90	6.0	14,300
3.7 - 7.4	5.44	14.5	60,100



Fig. 25. The scatter plots of  $E_{AC}/p$  vs.  $E_{tot}/p$  for (a)  $e^+e^- \rightarrow e^+e^-$  in the  $E_{cm}$  range of 6.4 to 7.4 GeV, (b)  $e^+e^- \rightarrow \mu^+\mu^-$  in the  $E_{cm}$ range of 6.4 to 7.4 GeV, (c)  $e^+e^- \rightarrow \mu$  hadrons in the  $E_{cm}$  range of 6.4 to 7.4 GeV and (d)  $e^+e^- \rightarrow \psi \rightarrow$  hadrons at  $E_{cm} = 3.098$  GeV.  $E_{AC}$  is the energy deposited in the active converters.  $E_{tot}$ is the total energy deposited in the lead-glass counter system. p is the momentum of the particle.

C. Particle Identification in the Magnetic Detector

A particle detected in the magnetic detector is identified as an electron (e) by the following criteria:

- 1) The momentum of the particle, p, is greater than 0.65 GeV/c.
- 2) The shower pulse height, H<sub>c</sub>, is greater than 50 (see App. A). A fixed lower limit on H<sub>c</sub> of 50 was used instead of a p-dependent limit for three reasons:
- The pulse height distribution for a fixed p is rather broad (see Fig. 31 and App. A).
- The relation in Eq. (61) could not be maintained precisely (see App. A).
- 3) The relation in Eq. (61) is only approximate. There are nonlinearities in the relations of  $H_c(p)$  to p below 1 GeV/c and above 2 or 2.5 GeV/c (see App. A).

For these reasons a fixed lower limit on  $H_c$  was easier to use, and losses and corrections easier to evaluate.

A lower limit on p of 0.65 GeV/c was used to reduce the loss of electrons whose pulse height was below 50.

A particle detected in the magnetic detector is identified as a muon  $(\mu)$  by the following criteria:

- 1) The momentum of the particle, p, is greater than 0.65 GeV/c.
- 2) The shower pulse height,  $H_c$ , is less than 50 (see App. A). We note that an e is defined first. Therefore if  $H_c$  is greater than 50, a particle is called an e.
- The particle has the proper angle to reach the active area of the muon chambers at level 1.

- 4) The muon chambers at level 1 fire at less than 3σ from the position of the projected track in the chambers. σ is defined as one standard deviation due to multiple scattering. It depends on the momentum of the track and the thickness of the material traversed. A particle detected in the magnetic detector is identified as a hadron (h) by the following criteria:
  - .
  - 1) The momentum of the particle, p, is greater than 0.65 GeV/c.
  - 2) The shower pulse height,  $H_c$ , is less than 50 (see App. A).
  - The particle has the proper angle to reach the active area of the muon chambers at level 1.
  - The particle is not identified as a muon by the muon chambers at level 1.

A particle detected in the magnetic detector is identified as a "no µ" (muon or hadron) by the following criteria:

- 1) The momentum of the particle, p, is greater than 0.65 GeV/c.
- 2) The shower pulse height,  $H_c$ , is less than 50 (see App. A).
- 3) The particle does not have the proper angle to reach the active area of the muon chambers at level 1.
- D. Event Selection

eµ and eh events were selected with the following criteria:

- 1) Two and only two charged particles are detected.
- One of the charged particles is detected in the lead-glass counter system and identified as an electron.
- The other charged particle is detected in the magnetic detector and identified as a muon or hadron.
- 4) There are no restrictions on the number of detected photons.

- 5) One and only one vertex is detected.
- 6) The charged particle detected in the lead-glass counter system has a momentum greater than 0.40 GeV/c  $(p_1 > 0.40 \text{ GeV/c})$ .
- 7) The charged particle detected in the magnetic detector has a momentum greater than 0.65 GeV/c ( $p_2 > 0.65$  GeV/c),
- 8) The two detected charged particles have opposite electric charge.
- The two detected charged particles do not hit the spark chamber support posts.

There are four sources of  $e\mu$  and eh events. They are:

- Misidentification of particles, decay of ordinary or strange hadrons, hadronic interaction and punchthrough:
- Photon conversion and Dalitz decay with one member of the pair misidentified as a hadron or muon;
- 3) Quantum electrodynamic processes such as

$$e^+e^- \rightarrow e^+e^-, e^+e^-\gamma$$
 and  $e^+e^-e^+e^-$  (31)

and

$$e^+e^- + \mu^+\mu^-$$
,  $\mu^+\mu^-\gamma$  and  $e^+e^-\mu^+\mu^-$ ; (32)

 Anomalous sources such as decays of charmed particles and heavy leptons.

The first three sources of  $e\mu$  and eh events are conventional sources and will be regarded as background sources of  $e\mu$  and eh events. The first background source and the anomalous sources of  $e\mu$  and eh events will be discussed in later sections. The background from photon conversion and Dalitz decay is reduced by eliminating electrons which have an opening angle of less than 8° with a particle of opposite charge. This eliminates  $e^+e^-$  pairs. The background from quantum electrodynamic processes is reduced by requiring that:

$$\theta_{cop1} > 20^{\circ}$$

1)

(33)

where  $\theta_{\mbox{copl}}$  is the coplanarity angle of the two prongs about the incident beams. It is defined as

$$\cos \theta_{copl} = -(\vec{n}_1 \times \vec{n}_+) \cdot (\vec{n}_2 \times \vec{n}_+) / (|\vec{n}_1 \times \vec{n}_+| \cdot |\vec{n}_2 \times \vec{n}_+|)$$
(34)

where  $\vec{n}_1$ ,  $\vec{n}_2$  and  $\vec{n}_+$  are unit vectors in the direction of motion of particle 1, particle 2 and the incident e<sup>+</sup> beam, respectively.

2)  $m_m^2 > 0.8 (GeV/c^2)^2$  for  $E_{cm} < 4.4 GeV$   $m_m^2 > 1.1 (GeV/c^2)^2$  for  $4.4 < E_{cm} < 6.4 GeV$  (35)  $m_m^2 > 1.5 (GeV/c^2)^2$  for  $E_{cm} > 6.4 GeV$ where  $m_m^2$  is the square of the missing mass recoiling against the

two prongs. It is defined as

$$m_m^2 = (E_{cm} - E_1 - E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$
 (36)

where  $E_i$ ,  $p_i$  are the energy and three-momentum of particle i.

### E. Background Event Selection

In order to correct for the background from misidentification of particles, decay of ordinary or strange hadrons, hadronic interaction and punchthrough, background events of the types ee,  $e(no \mu)$ , (no e)e,  $(no e)\mu$ , (no e)h and  $(no e)(no \mu)$  were selected with the same criteria as  $e\mu$  and eh events. The first particle listed is the particle detected in the lead-glass counter system and the second particle listed is the particle detected in the magnetic detector.

#### F. Uncorrected Data

Table XI presents the uncorrected number of charge zero and charge  $\pm 2$  two-prong events in four  $E_{\rm CM}$  regions. The charge  $\pm 2$  events are presented for comparison.

# TABLE XIA

The uncorrected number of charge zero two-prong events in four

E regions.

Type of	Photons	E range (GeV) c.m.			
event	detected	3.7 - 4.0	4.0 - 4.4	4.4 - 6.4	6.4 - 7.4
ee	no	11	3	8	19
еµ	no	1	7	8	11
eh	no	3	4	6	7
e(no μ)	no	0	0	0	0
(no e)e	no	7	6	18	22
(по е)µ	no	15	15	29	33
(no e)h	no	10	13	19	23
(no e)(no µ)	no	o	O	0	0
ee	yes	15	31	36	60
еµ	yes	3	4	4	7
eh	yes	6	6	8	8
e(noμ)	yes	0	0	O	1
(no e)e	yes	23	25	34	40
(no e)µ	yes	14	28	40	55
(no e)h	yes	60	54	81	56
(no e)(no µ)	yes	1	1	1	3

# TABLE XIB

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The uncorrected number of charge ±2 two-prong events in four

E regions.

Туре	Photono	E range (GeV)			
or event	detected	3.7 - 4.0	4.0 - 4.4	4.4 - 6.4	6.4 - 7.4
ee	no	0	1	Ō	1
eμ	no	0	0	0	0
eh	no	1	0	0	1
e(no μ)	no	0	0	0	0
(no e)e	no	1	0	2	0
(no e)µ	no	1	0	1	3
(no e)h	no	3	4	7	12
(no e)(no µ)	no	0	0	0	0
ee	yes	0	0	1	0
еµ	yes	0	0	0	0
eh	yes	o	1	1	2
e(no μ)	yes	o	O	0	0
(no e)e	yes	2	1	1	8
(no e)µ	yes	5	2	8	5
(no e)h.	yes	8	13	15	17
(no e) (no µ)	yes	0	o	0	1

# G. Misidentification Probabilities and Identification Efficiencies in

# the Lead-Glass Counter System

Table XIIA presents the misidentification probabilities and identification efficiencies in the lead-glass counter system. They are used to correct for the background from misidentification of particles, decay of ordinary or strange hadrons and hadronic interaction. These probabilities are averaged over the observed momentum spectrum.

The probability that an electron would be identified as an electron or a "no e"  $(P_{e \to e} \text{ or } P_{e \to (no e)})$  in the lead-glass counter system was determined from radiative Bhabha events of the type

$$e^+e^- + e^+e^-\gamma \tag{37}$$

with an electron in the lead-glass counter system. We determined  $P_{e \rightarrow e}$  from the number of electrons which passed the electron criteria and  $P_{e \rightarrow (no \ e)}$  from the number of electrons which did not pass the electron criteria.

eey events were selected with the following criteria:

- 1) Two and only two charged particles are detected.
- One of the charged particles is detected in the lead-glass counter system.
- The other charged particle is detected in the magnetic detector and identified as an electron.
- 4) One and only one photon is detected.
- The direction of the missing momentum points toward the shower counter which has fired.
- 6) One and only one vertex is detected.
- 7) The two detected charged particles have opposite electric charge.
- The two detected charged particles do not hit the spark chamber support posts.

### TABLE XIIA

The misidentification probabilities in the lead-glass counter system as described in the text.

Misidentification	E <sub>c.m.</sub> range (GeV)			
probabilities	3.7 - 4.0	4.0 - 4.4	4.4 - 6.4	6.4 - 7.4
P e+e	0.93	0.93	0.93	0.93
<sup>P</sup> e→(no e)	0.07	0.07	0.07	0.07
P <sub>(no e)→e</sub>	0.02	0.02	0.02	0.02
<sup>P</sup> (no e)→(no e)	0.98	0.98	0.98	·0.98

9) 
$$|m_m^2| < 0.5 (GeV/c^2)^2$$

where  $m_m^2$  is the square of the missing mass recoiling against the two prongs. It is defined in Eq. (36).

(38)

The probability that a hadron would be identified as an electron or a "no e" ( $P_{h \rightarrow e}$  or  $P_{h \rightarrow (no \ e)}$ ) in the lead-glass counter system was determined from multihadronic events from  $\psi(3095)$  decay, assuming no anomalous electron production at the  $\psi(3095)$ . Figure 25(d) shows the scatter plot of  $E_{AC}/p$  vs.  $E_{tot}/p$  for the reaction

$$\pm e^- \rightarrow \psi(3095) \rightarrow hadrons$$
 (39)

We determined  $P_{h \rightarrow e}$  from the number of hadrons which passed the electron criteria and  $P_{h \rightarrow (no \ e)}$  from the number of hadrons which did not pass the electron criteria. The probability that a muon will be identified as an electron ( $P_{\mu \rightarrow e}$ ) in the lead-glass counter system is much less than  $P_{h \rightarrow e}$ . Therefore  $P_{h \rightarrow e}$  and  $P_{h \rightarrow (no \ e)}$  are used as  $P_{(no \ e) \rightarrow e}$  and  $P_{(no \ e) \rightarrow (no \ e)}$ , respectively.

An important source of background for the anomalous electron signal is photon conversion or Dalitz decay in which one member of the  $e^+e^$ pair has a low momentum and is therefore undetected. This background can be expressed as an increase in the value of  $P_{(no\ e)\rightarrow e}$  by about 0.3%. This number was determined by measuring  $e^+e^-$  pairs with both particles detected, and then extrapolating to the case of  $e^+e^-$  pairs with one low-momentum electron. This background has already been included in the value of  $P_{(no\ e)\rightarrow e}$  in Table XIIA.

# in the Magnetic Detector

Table XIIB presents the misidentification probabilities and identification efficiencies in the magnetic detector. They are used to correct for the background from misidentification of particles, decay of ordinary or strange hadrons, hadronic interaction and punchthrough. These probabilities are averaged over the observed momentum spectrum.

The probability that an electron would be identified as an electron, muon, hadron, or "no  $\mu$ " ( $P_{e \rightarrow e}^{D}$ ,  $P_{e \rightarrow \mu}^{D}$ ,  $P_{e+h}^{D}$  or  $P_{e+(no \ \mu)}^{D}$ ) in the magnetic detector was determined from radiative Bhabha events (Eq. (37)) with both electrons in the magnetic detector. We determined  $P_{e \rightarrow e}^{D}$  from the number of electrons which were identified as electrons,  $P_{e+\mu}^{D}$  from the number of electrons which were identified as muons,  $P_{e+h}^{D}$  from the number of electrons which were identified as hadrons and  $P_{e+(no \ \mu)}^{D}$  from the number of electrons which were identified as hadrons and  $P_{e+(no \ \mu)}^{D}$  from the number of electrons which were identified as hadrons and  $P_{e+(no \ \mu)}^{D}$  from the number of electrons which were identified as hadrons and  $P_{e+(no \ \mu)}^{D}$  from the number of electrons which were identified as hadrons and  $P_{e+(no \ \mu)}^{D}$  from the number of electrons which were identified as hadrons are preserved.

eey events were selected with exactly the same criteria as eey events in Sec. VG, except that:

- 1) Both charged particles are detected in the magnetic detector.
- One of the detected charged particles is identified as an electron with a shower pulse height, H<sub>c</sub>, of greater than 75 (see App. A).

The probability that a muon would be identified as an electron, muon, hadron or "no  $\mu$ " ( $P^{D}_{\mu \rightarrow e}$ ,  $P^{D}_{\mu \rightarrow \mu}$ ,  $P^{D}_{\mu \rightarrow h}$  or  $P^{D}_{\mu \rightarrow (no \ \mu)}$ ) in the magnetic detector was determined from radiative muon pairs of the type

$$e^{\dagger}e^{-} \neq \mu^{\dagger}\mu^{-}\gamma \tag{40}$$

with both muons in the magnetic detector. We determined  $P^D_{\mu \rightarrow e}$  from the number of muons which were identified as electrons,  $P^D_{\mu \rightarrow u}$  from the number

## TABLE XIIB

The misidentification probabilities in the magnetic detector as described in the text.

Misidentification		E ra: c.m.	nge (GeV)	
probabilities	3.7 - 4.0	4.0 - 4.4	4.4 - 6.4	6.4 - 7.4
P D e+e	0.93	0.93	0.93	0.93
P D e→µ	0.011	0.011	0.011	0.011
P e≁h	0.056	0.056	0.056	0.056
P <sup>D</sup> e→(no μ)	0.003	0.003	0.003	0.003
₽ µ≁e	0.04	0.04	0.04	0.04
ք µ≁µ	0.86	0.86	0.86	0.86
P µ→h	0.08	0.08	0.08	0.08
Ρ μ→(no μ)	0.02	0.02	0,02	0.02
P h≁e	0.10	0.12	0.14	0.18
P h≁µ	0.14	0.16	0.17	0.18
P <sup>D</sup> h→h	0.69	0.64	0.61	0.56
P h→(no μ)	0.07	0.08	0.08	0.08

of muons which were identified as muons,  $P^D_{u \rightarrow h}$  from the number of muons

which were identified as hadrons and  $P^{D}_{\mu \neq n}$  from the number of muons which were identified as "no  $\mu$ "s.

 $\mu\mu\gamma$  events were selected with exactly the same criteria as eev events in Sec. VG, except that:

- 1) Both charged particles are detected in the magnetic detector.
- 2) One of the detected charged particles is identified as a muon with a shower pulse height,  $H_{c}$ , of less than 30 (see App. A).

The probability that a hadron would be identified as an electron, muon, hadron or "no  $\mu$ " ( $P_{h+e}^{D}$ ,  $P_{h+\mu}^{D}$ ,  $P_{h+h}^{D}$  or  $P_{h+(no \ \mu)}^{D}$ ) in the magnetic detector was determined from hadronic events with five or more charged prongs.  $e^+e^-$  pairs were eliminated by requiring the opening angle between any two tracks of opposite charge to be greater than 8°. All other prongs were assumed to be hadrons. We determined  $P_{h+e}^{D}$  from the number of hadrons which were identified as electrons,  $P_{h+\mu}^{D}$  from the number of hadrons which were identified as muons,  $P_{h+h}^{D}$  from the number of hadrons which were identified as hadrons and  $P_{h+(no \ \mu)}^{D}$  from the number of hadrons which were identified as "no  $\mu$ "s. These probabilities were calculated separately for each of the four  $E_{om}$  regions.

 $P_{h+e}^{D}$  and  $P_{h+\mu}^{D}$  are actually upper bounds since they include not only the effects of decay of ordinary or strange hadrons, hadronic interaction and punchthrough, but also any direct lepton production (from charmed particles or heavy leptons) in hadronic events with five or more charged prongs.

corrected The number for triggering efficiencies, geometric acceptances or kinematic cuts. ß charge zero two-prong events corrected for misidentification, but The errors DOL

are statistical.

(no e)h e, 0 0 e e(no μ) (no e)µ ğ e(no µ) 윧 (no e)μ (no e)e (no e) (no (no e)e e)h Type of event E Photons detected è ye. ě Yee yea Ë ц 뎡 B 뎡 B p g 11.9 15.6 15.7 12 -1.2 ο 5.8 2.2 3.7 ł 4.0 0 ... 3.8 ò 33.7 18. 13.8 17... 5.8 0 4.7 2.9 0.6 5.0 7.3 2.3 4.0 8 , est 14 1 ÷ σ 0 4.9 σ 0.8 ۍ 6 ω.5 2 4 ō range 132.4 4.4 20.4 8 26 28 13.2 (GeV) 08 7.1 Ň . I. 6.4 ý 9.4 œ 0 5.9 ð 9.9 ŝ Ψ 3.9 4.6 õ 6.4 94.6 44.5 65.5 30.6 10.6 36 8.7 0 ა. 8 Ç, ί. Γ 9.0 1.0 Т 1+ 7 4 5 5.2 6.7 œ 5 4. 5 œ ō ò -Ln uл

72

Table XIII presents the number of charge zero and charge ±2 twoprong events corrected for misidentification of particles, decay of ordinary or strange hadrons, hadronic interaction and punchthrough, but not corrected for triggering efficiencies, geometric acceptance or kinematic cuts. The corrected data were obtained by the following method.

We define two 1 x 8 column matrices: D, which gives the number of observed events, and A, which gives the number of actual events. Specifically:

$$D = \begin{cases} N_{o}(ee) & N_{a}(ee) \\ N_{o}(e\mu) & N_{a}(e\mu) \\ N_{o}(eh) & N_{a}(eh) \\ N_{o}(e(no \ \mu)) & N_{a}(e(no \ \mu)) \\ N_{o}((no \ e)e) & ; & A = N_{a}((no \ e)e) \\ N_{o}((no \ e)\mu) & N_{a}((no \ e)\mu) \\ N_{o}((no \ e)h) & N_{a}((no \ e)h) & (41) \\ N_{o}((no \ e)(no \ \mu)) & N_{a}((no \ e)(no \ \mu)) \end{cases}$$

Then D and A are related by an 8 x 8 matrix M

D = MA

where the elements of M are given by:

 $M_{ee \rightarrow ee} = P_{e \rightarrow e} P_{e \rightarrow e}^{D}$  $M_{ee \rightarrow e_{1}} = P_{e \rightarrow e} P_{e \rightarrow u}^{D}$  $M_{ee \rightarrow eh} = P_{e \rightarrow e} P_{e \rightarrow h}^{D}$  $M_{eu \rightarrow ee} = P_{e \rightarrow e} P_{u \rightarrow e}^{D}$  $M_{e\mu \rightarrow e\mu} = P_{e \rightarrow e} P_{\mu \rightarrow \mu}^{D}$  $M_{e\mu \rightarrow eh} = P_{e \rightarrow e} P_{\mu \rightarrow h}^{D}$ 

71

# I. Corrected Data

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Туре	2		E ran	ge (GeV)	
event	detected	3.7 - 4.0	4.0 - 4.4	4.4 - 6.4	6.4 - 7.4
ee	no	-0.2 ± 0.4	1.2 ± 1.1	0.0 ± 0.1	$0.9 \pm 1.2$
еµ	IJ.	-0.3 ± 0.6	$0.0 \pm 0.2$	0.0 ± 0.2	$-0.4 \pm 0.7$
eh	no	$1.5 \pm 1.5$	$-0.2 \pm 0.6$	$-0.2 \pm 0.6$	$1.4 \pm 2.1$
e(no µ)	no	$-0.1 \pm 0.3$	$0.0 \pm 0.1$	$0.0 \pm 0.1$	$-0.1 \pm 0.3$
(no e)e	no	$0.6 \pm 1.3$	$-0.9 \pm 1.0$	$0.4 \pm 2.1$	-4.5 ± 2.2
(no e)µ	no	0.5 ± 1.5	$-1.3 \pm 1.2$	$-1.2 \pm 2.1$	-1.2 ± 3.1
(no e)h	no	$4.3 \pm 2.6$	$6.7 \pm 3.3$	$11.9 \pm 4.5$	$22.7 \pm 6.5$
(no e) (no µ)	no	$-0.3 \pm 0.6$	$-0.5 \pm 0.7$	-0.9 ± 1.0	$-1.8 \pm 1.3$
¢ Ø	yes	0.0 ± 0.1	$-0.2 \pm 0.4$	$1.0 \pm 1.2$	-0.8 ± 0.9
μ	yes	$-0.1 \pm 0.3$	-0.3 ± 0.6	$-0.4 \pm 0.7$	-0.8 ± 1.0
eh	yes	$-0.2 \pm 0.6$	$1.2 \pm 1.8$	$1.2 \pm 2.0$	3.3 ± 2.8
e(no µ)	уез	$0.0 \pm 0.1$	$-0.1 \pm 0.3$	$-0.1 \pm 0.3$	$-0.3 \pm 0.5$
(no e)e	уез	$0.8 \pm 2.0$	$-1.6 \pm 2.0$	$-3.0 \pm 2.4$	$2.7 \pm 4.0$
(no e)µ	yes	$4.0 \pm 3.1$	$-1.6 \pm 2.8$	4.5 ± 4.1	-0.7 ± 3.9
(no e)h	yes	$11.4 \pm 4.3$	$21.2 \pm 5.8$	$25.0 \pm 6.6$	$31.0 \pm 7.6$
(no e) (no µ)	yes	$-0.9 \pm 1.0$	$-1.6 \pm 1.3$	$-2.1 \pm 1.5$	-1.4 ± 1.9

corrected The number for triggering °f charge efficiencies, geometric ±2 two-prong events corrected accpetances or kinematic cuts. for misidentification, but The not

TABLE

XIIIB

errors are statistical.

 $M_{eh \rightarrow ee} = P_{e \rightarrow e} P_{h \rightarrow e}^{D}$  $M_{eh \rightarrow e\mu} = P_{e \rightarrow e} P_{h \rightarrow \mu}^{D}$  $M_{eh \rightarrow eh} = P_{e \rightarrow e} P_{h \rightarrow h}^{D}$ etc.

We then invert the matrix M to yield

$$A = M^{-1}D \tag{44}$$

ί,

(For a numerical interpretation of the matrix M, see App. C.)

74

Taking D from Table XI and calculating M from Table XII, we find A for the four sets of data as given in Table XIII. Since there is no constraint on the elements of matrix A, negative numbers may, and do, appear. We note that  $N_a(e(no \ \mu))$  and  $N_a((no \ e)(no \ \mu))$  are consistent with zero within the errors. This is as it should be, because "no  $\boldsymbol{\mu}^{\prime\prime}$ is a designation for an observed particle type, and an actual particle type can only be e,  $\mu$  or h. The consistency of  $N_{}_{a}(e(no~\mu))$  and  $N_{a}((no e)(no \mu))$  with zero means that our misidentification probabilities are correct within the statistical errors of this analysis.

The same procedure was repeated for the data with detected photons and the data with charge ±2. We note that there are no significant anomalous signals in the charge ±2 eµ or eh events.

### VI. RESULTS

# A. Charm Production

One of the anomalous sources of eµ and eh events is the semileptonic decay of charmed particles.

$$e^+e^- + c + c + (hadrons)$$
 (45)  
 $\downarrow ev_e hadrons + v_\mu hadrons$ 

and

$$e^+e^- \rightarrow c$$
 +  $\overline{c}$  + (hadrons) (46)  
+  $e_{\nu_a}$  hadrons + hadrons

where in the first case, the hadrons escape detection and in the second case, all but one of the charged hadrons escape detection.

In order to determine the contribution to the anomalous two-prong ex signal from charm production, a Monte Carlo simulation program was set up with the following criteria:

1) The assumed production processes are:<sup>28</sup>

$$e^{+}e^{-} \rightarrow D\overline{D} \qquad \text{for } 3.7 < E_{cm} < 4.0 \text{ GeV}$$

$$e^{+}e^{-} \rightarrow D^{*}\overline{D}^{*} \qquad \text{for } 4.0 < E_{cm} < 4.4 \text{ GeV} \qquad (47)$$

$$e^{+}e^{-} \rightarrow D^{*}\overline{D}^{*} \qquad \text{for } 4.4 < E_{cm} < 6.4 \text{ GeV}$$

$$e^{+}e^{-} \rightarrow D^{*}\overline{D}^{*}\pi\pi \qquad \text{for } 6.4 < E_{cm} < 7.4 \text{ GeV}$$

This assumption is based on the existing experimental evidence on the mechanism of D meson production.

- 2) The assumed decay processes are given in Eqs. (45) and (46) with the branching fractions of  $D^*$  and D listed in Table XIV.
- The produced charged multiplicity distributions for D decays agree with the experimental results<sup>29</sup> given in Fig. 26.
- 4) The observed total charged multiplicity distributions agree with

# TABLE XIVA

The branching fractions of  $D^*$  in the Monte Carlo calculation to determine the contribution to the anomalous two-prong signal from charm production. (Ref. 29)

Me	ode	Branching fraction
D*0	D <sup>o</sup> γ	0.54
	D <sup>ο</sup> π <sup>ο</sup>	0.46
D <b>*+</b>	σ <sup>+</sup> γ	0.33
	D <sup>0</sup> π <sup>+</sup>	0.67

# TABLE XIVB

77

The semileptonic branching fractions of D in the Monte Carlo calculation to determine the contribution to the anomalous two-prong signal from charm production. (Ref. 28)

	Mode	Branching fraction
Do	K <sup>-</sup> e <sup>+</sup> ν <sub>e</sub>	0.50
	K <sup>*-</sup> e <sup>+</sup> ν <sub>e</sub> (V-A)	0.50
D+	κ <sup>o</sup> e <sup>+</sup> ν <sub>e</sub>	0.50
	$\overline{K^{\star o}} e^+ v_e (V-A)$	0.50

# TABLE XIVC

5

The non-leptonic branching fractions of D in the Monte Carlo calculation to determine the contribution to the anomalous two-prong signal from charm production. (Ref. 29)

	Mode	Branching fraction
Do	K <sup>-</sup> π <sup>+</sup>	0.57
	$\overline{K^{O}} \pi^{+} \pi^{-}$	0.35
	K <sup>-</sup> π <sup>+</sup> π <sup>-</sup> π <sup>+</sup>	0.08
D+	$\overline{K^{O}} \pi^{+}$	0.57
	К <sup>-</sup> # <sup>+</sup> # <sup>+</sup>	0.43



Fig. 26. The observed and true (unfolded) charged multiplicity distributions for D decays. (Ref. 29)

the multiprong electron results<sup>28</sup> given in Fig. 27.

- The number of neutral kaons is equal to the number of charged kaons.
- 6) For events with two or more charged prongs,

$$|p_1 > 0.40 \text{ GeV/c}$$
 (48)  
 $|\cos \theta_1| < 0.5$ 

where  $p_1$  is the momentum of the electron and  $\theta_1$  is the angle between the electron and the e<sup>+</sup> beam direction. The angular cut is used to simulate the geometric acceptance of the lead-glass counter system.

7) For events with two charged prongs,

$$|\rho_2 > 0.65 \text{ GeV/c}$$

$$|\cos \theta_2| < 0.6$$
(49)

where  $p_2$  is the momentum of the muon or hadron and  $\theta_2$  is the angle between the muon or hadron and the e<sup>+</sup> beam direction. The angular cut is used to simulate the geometric acceptance of the magnetic detector. In addition,

$$\theta_{copl} > 20^{\circ}$$
 $m_{m}^{2} > 0.8 (GeV/c^{2})^{2} \text{ for } E_{cm} < 4.4 GeV$ 
 $m_{m}^{2} > 1.1 (GeV/c^{2})^{2} \text{ for } 4.4 < E_{cm} < 6.4 GeV$ 
 $m_{m}^{2} > 1.5 (GeV/c^{2})^{2} \text{ for } E_{cm} > 6.4 GeV$ 
(50)

where  $\theta_{cop1}$  is defined in Eq. (34) and  $m_m^2$  is defined in Eq. (36).

The contribution to the anomalous two-prong ex signal from charm production was determined from the observed total charged multiplicity distributions in the Monte Carlo unfold. 10% of this contribution actually comes from the following process:



Fig. 27. The observed total charged multiplicity distributions for multiprong electron data (open dot) and Monto Carlo calculations (closed dot) with three or more prongs in four E<sub>cm</sub> regions. Both sets of points are normalized to one for comparison.  $e^{+}e^{-} \rightarrow \tau^{+} \qquad + \tau^{-} \qquad (51)$   $\downarrow_{\bullet e^{+}\nu_{e}\overline{\nu_{\tau}}} \qquad \downarrow_{\bullet \nu_{\tau}} (hadrons)^{-}$ 

where all but one of the charged hadrons escape detection.

82

We estimate that 10% of this contribution goes to the anomalous two-prong  $e\mu$  signal and 90% of this contribution goes to the anomalous two-prong eh signal. The results are presented in Table XV.

### B. Heavy Lepton Production

Table XVI presents the observed production cross sections for eu events with no detected photons,  $\sigma_{e\mu}$ , and eh events with any number of detected photons,  $\sigma_{eh}$ . There is a significant anomalous signal above the charm background. The following model of heavy lepton production and decay is used to explain this anomalous signal.

$$e^{+}e^{-} \rightarrow \tau^{+}\tau^{-}$$

$$\tau^{\pm} \rightarrow e^{\pm}\nu_{e}\nu_{\tau}$$

$$\tau^{\mp} \rightarrow \mu^{\mp}\nu_{\mu}\nu_{\tau}$$

$$\tau^{\mp} \rightarrow h^{\mp} + \nu_{\tau} + \geq 0 \gamma's$$
(52)

The observed production cross sections for eµ and eh events from the above processes are

$$\sigma_{eu}(s) = 2A_{eu}(s) B_e B_u \sigma_{\tau\tau}(s)$$
(53a)

$$\sigma_{eh}(s) = 2A_{eh}(s) B_e B_h \sigma_{\tau\tau}(s)$$
(53b)

where  $\sigma_{\tau\tau}$  is the point particle pair production cross section for a heavy lepton  $\tau$  with spin 1/2. It is defined as

$$\sigma_{\tau\tau}(s) = \frac{2\pi\alpha^2\beta(3-\beta^2)}{3s}$$
(54)

where  $\alpha$  is the fine structure constant and  $\beta c$  is the velocity of the  $\tau$  and  $s \approx E_{cm}^2$ .  $\sigma_{\tau\tau}$  can also be written as

### TABLE XV

The calculated background contribution to the anomalous two-prong eu and eh signals from the semileptonic decay of charm particles.

R	Charm background (pb)		
C.m.	eµ events	eh events	
3.7 - 4.0	$0.2 \pm 0.2$	1.6 ± 1.9	
4.0 - 4.4	$0.1 \pm 0.1$	1.3 ± 0.9	
4.4 - 6.4	$0.1 \pm 0.1$	0.8 ± 0.6	
6.4 - 7.4	$0.1 \pm 0.1$	0.6 ± 0.6	

84

# TABLE XVI

The observed production cross sections for eµ events,  $\sigma_{e\mu}$ , and for eh events,  $\sigma_{eh}$ , in four  $E_{c.m.}$  regions before and after charm background subtraction. The cross sections are corrected for misidentification, but not corrected for triggering efficiencies, geometric acceptances or kinematic cuts. The errors are statistical.

	σ <sub>eμ</sub> (pb)		σ <sub>eh</sub> (pb)	
E <sub>c.m.</sub> range (GeV)	Before charm background subtraction	After charm background subtraction	Before charm background subtraction	After charm background subtraction
3.7 - 4.0	0.1 ± 0.7	-0.1 ± 0.7	4.0 ± 2.3	2.4 ± 3.0
4.0 - 4.4	$2.9 \pm 1.4$	$2.8 \pm 1.4$	3.9 ± 2.4	2.6 ± 2.6
4.4 - 6.4	2.0 ± 1.1	1.9 ± 1.1	4.1 ± 2.0	3.3 ± 2.1
6.4 - 7.4	1.8 ± 0.8	1.7 ± 0.8	2.5 ± 1.5	1.9 ± 1.6

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$$\sigma_{\tau\tau}(s) = \sigma_{\mu\mu}(s) \frac{3\beta - \beta^3}{2}$$
(55)

where

 $\sigma_{\mu\mu}(s) = \frac{86.8}{s} nb$  (56)

Table XVII presents  $\sigma_{\tau\tau}$  for a heavy lepton  $\tau$  with  $m_{\tau} = 1.85 \text{ GeV/c}^2$ .

85

 $A_{e\mu}$  and  $A_{eh}$  are the acceptances for  $e\mu$  and eh events, respectively. They include triggering efficiencies, geometric acceptances and kinematic cuts. For the purpose of calculating the acceptances, we assume V-A coupling,  $m_{\nu_{\tau}} = 0$  and  $m_{\tau} = 1.85 \text{ GeV/c}^2$ . In calculating  $A_{eh}$ , we also assume that only the decays  $\tau^- \neq \pi^- \nu_{\tau}$  and  $\tau^- \neq \rho^- \nu_{\tau}$  contribute to two-prong eh events. We expect these two decay modes to constitute 77% of the  $\tau \rightarrow$  one charged hadron decays.<sup>16</sup> Table XVIII presents  $A_{e\mu}$  and  $A_{eh}$  with the above assumptions.

 $B_e$ ,  $B_\mu$  and  $B_h$  are the branching ratios for  $\tau^- + v_\tau e^{-\overline{v}}_e$ ,  $\tau^- + v_\tau \mu^- \overline{v}_\mu$  and  $\tau^- + h^- + v_\tau^- + \ge 0$  Y's respectively. We computed  $B_e$ from Eq. (53a) using  $\sigma_{e\mu}$  from Table XVI,  $\sigma_{\tau\tau}$  from Table XVII and  $A_{e\mu}$ from Table XVIII and assuming  $B_e^- = B_\mu$ . The values of  $B_e$  weighted by their errors were combined to give the average  $B_e$ . We then computed  $B_h$  from Eq. (53b) using  $\sigma_{eh}$  from Table XVI,  $\sigma_{\tau\tau}$  from Table XVII,  $A_{eh}$ from Table XVIII and the average  $B_e$ . The values of  $B_h$  weighted by their errors were combined to give the average  $B_h$ . The results are presented in Table XIX. Within the statistical errors, the results in the  $E_{cm}$  region of 3.7 to 4.0 GeV are consistent with the results in the other three  $E_{cm}$  regions.

Including an estimated 20% systematic error (Table XX), the average  $B_e = 0.21 \pm 0.05$  and the average  $B_h = 0.28 \pm 0.13$ , assuming  $m_{\tau} = 1.85 \text{ GeV/c}^2$  and correcting for charm background.  $B_e$  and  $B_h$  are not

86

### TABLE XVII

The point particle pair production cross section,  $\sigma_{\tau\tau}$ , for a heavy lepton  $\tau$  with  $m_{\tau} = 1.85 \text{ GeV/c}^2$  in four  $E_{c.m.}$  regions.

E <sub>c.m.</sub> range (GeV)	σ <sub>ττ</sub> (pb)
3.7 - 4.0	1840
4.0 - 4.4	3200
4.4 - 6.4	3000
6.4 - 7.4	1760

## TABLE XVIII

The acceptances  $A_{e\mu}$  and  $A_{eh}$ , which include triggering efficiencies, geometric acceptances and kinematic cuts, for  $e\mu$  and eh events respectively, in four  $E_{c.m.}$  regions. The assumptions used for the calculation of the acceptances are described in the text.

E <sub>c.m.</sub> range (GeV)	A eµ	A <sub>eh</sub>
3.7 - 4.0	0.0089	0.0088
4.0 - 4.4	0.0091	0.0091
4.4 - 6.4	0.0094	0.0091
6.4 - 7.4	0.0098	0.0089

TABLE XIX

The branching ratios  $B_e$  and  $B_h$  for  $\tau \rightarrow \nu_{\tau} = \nu_e$  and  $\tau \rightarrow h^- + \nu_{\tau} + \geq 0$  y's respectively before and after charm background subtraction. The assumptions used for the calculation of the branching ratios are described in the text. The errors are statistical.

··· ···	В	e <u> </u>	B <sub>h</sub>		
E <sub>c.m.</sub> range (GeV)	Before charm background subtraction	After charm background subtraction	Before charm background subtraction	After charm background subtraction	
3.7 - 4.0	0.06 ± 0.21		0.59 ± 0.35	0.35 ± 0.44	
4.0 - 4.4	$10.22 \pm 0.05$	0.22 ± 0.06	0.32 ± 0.20	0.21 ± 0.21	
4.4 - 6.4	0.19 ± 0.05	0.18 ± 0.05	0.36 ± 0.18	0.29 ± 0.19	
6.4 - 7.4	0.23 ± 0.05	0.22 ± 0.05	$0.38 \pm 0.23$	0.29 ± 0.25	
Average	0.21 ± 0.03	0.21 ± 0.03	0.38 ± 0.11	0.28 ± 0.12	

## TABLE XX

The estimated maximum systematic errors on the branching ratios

Be and B.

<u></u>	Be	B <sub>h</sub>
Systematic error due to luminosity counter calibra- tion	± 0.02	± 0.03
Systematic error due to mis- identification probabilities and identification efficiencies in the lead-glass counter system	± 0.02	± 0.03
Systematic error due to misiden- tification probabilities and identification efficiencies in the magnetic detector	± 0.02	± 0.03
Systematic error due to Monte Carlo calculation of the accept- ances	± 0.02	± 0.03
Total systematic error if combined in quadrature	± 0.04	± 0.06

sensitive to variations in  $m_{\tau}$  by several hundred MeV/c<sup>2</sup>.  $B_e$  is consistent with previous results (Table VII) and the theoretical value of  $0.16^{16}$  within the error.  $B_h$  is consistent with the theoretical value of  $0.43^{16}$  within the error. It is different from the published result<sup>30</sup> because of the charm background correction and an increase in statistics from 8.6 pb<sup>-1</sup> to 14.5 pb<sup>-1</sup>.

The theory predicts  $B(\tau \rightarrow \text{ one charged prong } + \nu_{\tau} + \ge 0 \gamma's)$  to be 0.75.<sup>16</sup> PLUTO has found it to be 0.69 ± 0.14.<sup>13</sup> DASP has found it to be 0.65 ± 0.12.<sup>11</sup> DELCO has found it to be 0.69 ± 0.06.<sup>5</sup> In this analysis, we have found it to be 0.70 ± 0.15.

# C. $\underline{\tau} \rightarrow \pi \nu$ Decay Mode

It is reasonable to assume that eh events with no detected photons come from the following processes:

$$e^{+}e^{-} \rightarrow \tau^{+}\tau^{-}$$

$$\tau^{\pm} \rightarrow e^{\pm}\nu_{e}\nu_{\tau}$$

$$\tau^{\mp} \rightarrow \pi^{\mp}\nu_{\tau}$$
(57)

and eh events with detected photons come from the following processes:



However, it is possible that eh events with no detected photons actually come from Eq. (58) where both photons escape detection. The magnitude of this effect is obtained from a Monte Carlo calculation and listed in Table XXI. The number of eh events without photons and the observed

## TABLE XXI

The fractions of events as described by Eq. (58) where both photons

# escape detection.

E range c.m. (GeV)	Fraction of events where both photons escape detection
3.7 - 4.0	0.41 ± 0.04
4.0 - 4.4	0.39 ± 0.04
4.4 - 6.4	0.38 ± 0.04
6.4 - 7.4	0.38 ± 0.04

production cross section for eh events without photons corrected for this background are listed in Table XXII. Because of the large error, we cannot make a statement on the existence of the  $\tau^- + \pi^- v_{\tau}$  decay mode.

# D. $\tau \rightarrow e \gamma$ , $\mu \gamma$ Decay Modes

We have assumed that eu events with no detected photons come from the following processes:

$$e^{+}e^{-} \rightarrow \tau^{+}\tau^{-}$$

$$\tau^{\pm} \rightarrow e^{\pm}\nu_{e}\nu_{\tau}$$

$$\tau^{\mp} \rightarrow \mu^{\mp}\nu_{\mu}\nu_{\tau}$$
(59)

We might also assume that  $e_{\mu}$  events with detected photons come from the following processes:

$$e^{+}e^{-} + \tau^{+}\tau^{-}$$

$$\tau^{\pm} + e^{\pm}\gamma$$

$$\tau^{+} + \mu^{+}\gamma$$
(60)

However, it is possible that  $e\mu$  events with detected photons actually come from Eq. (59), where there are extra shower counters latching. From a study of very collinear Bhabha and muon pair events with the momentum of each track very close to the beam energy, we have found that an electron track has an 8% chance of having an extra shower counter latching and a muon track has a 2.5% chance. Therefore an  $e\mu$  event has a 10% chance of having extra shower counters latching. The number of  $e\mu$  events with photons and the observed production cross section for  $e\mu$  events with photons corrected for this background are listed in Table XXIII. There is no evidence for the existence of the  $\tau^- + e^-\gamma$ ,  $\mu^-\gamma$  decay modes.

### TABLE XXIII

The number of eh events without photons and the observed production cross section for eh events without photons corrected for misidentification and the background described in Sec. VIC, but not corrected for triggering efficiencies, geometric acceptances or kinematic cuts. The errors are statistical.

TABLE XXII

E range c.m. (GeV)	Number of eh events without photons	Observed production cross section for eh events without photons
3.7 - 4.0	-0.7 ± 4.3	-0.3 ± 1.9
4.0 - 4.4	$2.0 \pm 4.8$	0.8 ± 1.9
4.4 - 6.4	3.7 ± 5.9	1.0 ± 1.6
6.4 - 7.4	5.4 ± 7.0	0.9 ± 1.2

The number of  $e\mu$  events with photons and the observed production cross section for  $e\mu$  events with photons corrected for misidentification and the background described in Sec. VID, but not corrected for triggering efficiencies, geometric acceptances or kinematic cuts. The errors are statistical.

94

	E range c.m. (GeV)	Number of eµ events with photons	Observed production cross section for eµ events with photons
	3.7 - 4.0	2.2 ± 2.5	1.0 ± 1.1
	4.0 - 4.4	2.1 ± 2.9	$0.8 \pm 1.2$
	4.4 - 6.4	1.3 ± 3.1	0.4 ± 0.8
-	6.4 - 7.4	4.1 ± 3.8	0.7 ± 0.6

In a different analysis<sup>31</sup> of the data, the 90% confidence level upper limit on the branching ratio was found to be 0.026 for the  $\tau^- \rightarrow e^-\gamma$  decay mode and 0.013 for the  $\tau^- + \mu^-\gamma$  decay mode.

# E. $\underline{\tau} \rightarrow \underline{A}_1 \underline{\nu}_1$ Decay Mode

In a different analysis<sup>32</sup> of the data in conjunction with previous data from the SLAC-LBL magnetic detector, the branching ratio for the  $\tau^- \rightarrow "A_1"^- v_{\tau}$  decay mode was found to be 0.12 ± 0.09.

### F. Excitation Functions

Figure 28 shows the observed production cross sections for eµ events,  $\sigma_{e\mu}$ , and for eh events,  $\sigma_{eh}$ , vs.  $E_{cm}$  before and after charm background subtraction. The cross sections are corrected for misidentification, but not corrected for triggering efficiencies, geometric acceptances or kinematic cuts. The curves are the theoretical predictions including triggering efficiencies, geometric acceptances and kinematic cuts for a heavy lepton  $\tau$  with  $m_{\tau} = 1.80$ , 1.85 and 1.90 GeV/c<sup>2</sup>. We note that the observed production cross sections have the expected energy dependence for a heavy lepton  $\tau$  with a mass between 1.80 and 1.90 GeV/c<sup>2</sup>.

### G. Momentum and Coplanarity Distributions

Figure 29 shows the r distributions for the electrons of the anomalous eµ and eh events, the muons of the anomalous eµ events and the hadrons of the anomalous eh events before and after charm background subtraction. The distributions are corrected for misidentification, but not corrected for triggering efficiencies, geometric acceptances or kinematic cuts. The curves are the theoretical predictions including







Fig. 29. The r distributions (eq. 16) for the electrons of the anomalous  $e\mu$  and eh events, the muons of the anomalous  $e\mu$  events and the hadrons of the anomalous eh events (a) before and (b) after charm background subtraction. The curves are the theoretical predictions including triggering efficiencies, geometric acceptances and kinematic cuts for a heavy lepton  $\tau$  with  $m_{\tau} = 1.85 \text{ GeV/c}^2$ ,  $m_{\nu_{\tau}} = 0$  and V-A coupling. In these plots, the four  $E_{\rm Cm}$  regions have been combined. The hadron curve has been calculated with the assumptions explained in the text.

triggering efficiencies, geometric acceptances and kinematic cuts for a heavy lepton  $\tau$  with  $m_{\tau} \approx 1.85 \text{ GeV/c}^2$ ,  $m_{\nu_{\tau}} \approx 0$  and V-A coupling. The hadron curve has been calculated with the assumption that only the decays  $\tau^- \neq \pi^- \nu_{\tau}$  and  $\tau^- \neq \rho^- \nu_{\tau}$  contribute to two-prong eh events. The curves are normalized to the number of events in each plot. The parameter r is defined in Eq. (16).

Figure 30 shows the  $\theta_{copl}$  distribution for all the anomalous twoprong ex events before charm background subtraction. The distribution is corrected for misidentification, but not corrected for triggering efficiencies, geometric acceptances or kinematic cuts. The curve is the theoretical prediction including triggering efficiencies, geometric acceptances and kinematic cuts for a heavy lepton  $\tau$  with  $m_{\tau} = 1.85 \text{ GeV/c}^2$ ,  $m_{v_{\tau}} = 0$  and V-A coupling. The curve is normalized to the number of events in the plot. The parameter  $\theta_{copl}$  is defined in Eq. (34).

# VII. CONCLUSIONS

- 1) We have confirmed previous observations<sup>1-14</sup> of anomalous twoprong eµ events using a lead-glass counter system with good electron identification. The branching ratio for  $\tau^{-} + v_{\tau} e^{-} \overline{v_{e}}$  was measured to be 0.21 ± 0.05.
- 2) We have reported for the first time anomalous two-prong eh events with any number of detected photons. The branching ratio for  $\tau^- + h^- + \nu_{\tau} + \ge 0 \gamma$ 's was measured to be 0.28 ± 0.13.
- 3) We have shown that charm production contributes only a minority of the anomalous two-prong signal.
- 4) We have shown that the majority of the anomalous two-prong signal is consistent with heavy lepton production.
- 5) The branching ratios, excitation functions, momentum and coplanarity distributions are consistent with those expected from the heavy lepton T.



Fig. 30. The  $\theta_{cop1}$  distribution (eq. 34) for all the anomalous twoprong ex events before charm background subtraction. The curve is the theoretical prediction including triggering efficiencies, geometric acceptances and kinematic cuts for a heavy lepton  $\tau$  with  $m_{\tau} = 1.85 \text{ GeV/c}^2$ ,  $m_{V_{\tau}} = 0$  and V-A coupling. In this plot, the four  $E_{CM}$  regions have been combined.

### APPENDIX A: SHOWER COUNTER CALIBRATION

The 21 shower counters were calibrated using Bhabha scattering events ( $e^+e^- \rightarrow e^+e^-$ ) in the  $\psi(3095)$  data. Two sets of  $\psi(3095)$  data were taken during the progress of the experiment: one during the fall cycle and one during the spring cycle.

Figure 31 shows the distributions of the shower pulse heights  $H_c$  for Bhabha scattering events in the  $\psi(3095)$  data excluding 10% of the counter width at each azimuthal edge and for the full counter length. Data from all 21 shower counters have been folded together. Part (a) shows the fall cycle data with an average shower pulse height  $\langle H_c \rangle = 132$  and a resolution  $\sigma_{H_c}/\langle H_c \rangle = 33\%$ . Part (b) shows the spring cycle data with  $\langle H_c \rangle = 150$  and  $\sigma_{H_c}/\langle H_c \rangle = 30\%$ .

The attenuation lengths of the 21 shower counters were calculated using uncorrected ADC pulse heights from the photomultipliers at the north and south ends of the shower counters. The ratios of the north and south pulse heights were used. The 6 scintillation counters which replaced 3 shower counters had infinity as their attenuation lengths.

The gain constants of the 42 photomultiplier tubes were adjusted to give an average gain of one and to give each shower counter the same average shower pulse height. The gain constants of the 6 photomultiplier tubes for the scintillation counters were adjusted to give each scintillation counter the same average pulse height.

A correction factor  $f_c$  was used to scale the average shower pulse height  ${}^{H}c^{>}$  to the value given in previous magnetic detector experiments.



Fig. 31. The distributions of the shower pulse heights  $H_c$  for Bhabha scattering events in the  $\psi(3095)$  data excluding 10% of the counter width at each azimuthal edge and for the full counter length. Data from all 21 shower counters have been folded together. Part (a) shows the fall cycle data and part (b) shows the spring cycle data.

The corrected average shower pulse height  $\langle H_C \rangle$  is defined in units such that for an electron of momentum p

(61)

<H\_(p)> 2 100 p

where p is in GeV/c.

APPENDIX B: SHOWER COUNTER EFFICIENCY

Cosmic ray data were collected during special runs in which the shower counters were removed from the hardware trigger requirement. The shower counter efficiency was then determined simply according to whether the counter struck by a cosmic ray was latched or not. Two sets of cosmic ray data were obtained for this purpose: one at the beginning of the fall cycle and one at the beginning of the spring cycle.

Figure 32 shows the shower counter cosmic ray efficiency vs. the longitudinal position Z on the counter for the full counter width. Figure 33 shows the shower counter cosmic ray efficiency vs. the longitudinal position Z on the counter excluding 5% of the counter width at each azimuthal edge. Figure 34 shows the shower counter cosmic ray efficiency vs. the azimuthal position  $f_{\phi}$  on the counter for the full counter length. Data from all 21 shower counters and 6 scintillation counters have been folded together. Table XXIV shows the shower counter cosmic ray efficiency in each shower counter for the full counter length and counter width. Counters 12, 13 and 14 are scintillation counters. Part (a) shows the fall cycle (10/76) data with 4864 events and part (b) shows the spring cycle (2/77) data with 16,657 events.

Figures 32 and 33 show a clear Z dependence in the shower counter cosmic ray efficiency due to the attenuation of the scintillation light. Figure 34 shows a correlation between inefficiency and the azimuthal edge.



Fig. 32. The shower counter cosmic ray efficiency vs. the longitudinal position Z on the counter for the full counter width. Data from all 21 shower counters and 6 scintillation counters have been folded together. Part (a) shows the fall cycle data and part (b) shows the spring cycle data.



Fig. 33. The shower counter cosmic ray efficiency vs. the longitudinal position Z on the counter excluding 5% of the counter width at each azimuthal edge. Data from all 21 shower counters and 6 scintillation counters have been folded together. Part (a) shows the fall cycle data and part (b) shows the spring cycle data.

# TABLE XXIVA

The shower counter cosmic ray efficiency in each shower counter for the full counter length and counter width. Counters 12, 13 and 14 are scintillation counters. The efficiency averaged over all the shower counters is 0.967 for the fall cycle data.

Counter Number	Number of events in each counter	Efficiency
1	15	1.000
2	37	1.000
3	160	0.931
4	508	0.969
5	705	0.957
6	538	0.967
7	595	0.961
8	802	0.953
9	725	0.921
10	493	0.943
11	251	0.904
12	45	1.000
13	11	1.000
14	53	1,000
15	248	0.964
16	629	0,975
17	542	0.956
18	537	0.959
19	567	0.974
20	773	0.970
21	663	0.980
22	539	0.978
23	238	0.971
24	51	0.980
	-	-



Fig. 34. The shower counter cosmic ray efficiency vs. the azimuthal position  $f_{\phi}$  on the counter for the full counter length. Data from all 21 shower counters and 6 scintillation counters have been folded together. Part (a) shows the fall cycle data and part (b) shows the spring cycle data.

### TABLE XXIVB

The shower counter cosmic ray efficiency in each shower counter for the full counter length and counter width. Counters 12, 13 and 14 are scintillation counters. The efficiency averaged over all the shower counters is 0.930 for the spring cycle data.

Counter number	Number of events in each counter	Efficiency
1	14	1.000
2	149	0.879
3	692	0.870
4	1452	0.935
5	1969	0,955
6	2519	0.912
7	2670	0.928
8	2764	0.880
9	2240	0.894
10	1704	0.898
11	477	0.849
12	17	0.882
13	53	0.943
14	231	0.952
15	804	0.953
16	1514	0.940
17	2056	0.951
18	2390	0.956
19	2560	0.964
20	2786	0.956
21	2111	0.957
22	1624	0.959
23	449	0.938
24	62	0.968

# APPENDIX C: MATRIX OF MISIDENTIFICATION PROBABILITIES

In the  $E_{cm}$  region of 3.7 to 4.0 GeV, the matrix of misidentification probabilities M has the following numerical elements:

1	0.87	0.04	0.09	0.00	0.02	0.00	0.002	0.00	
	0.01	0.80	0.13	0.00	0.00	0.02	0.003	0.00	
	0.05	0.07	0.64	0.00	0.00	0.00	0.014	0.00	
	0.00	0.02	0.07	0.93	0.00	0.00	0.001	0.02	(62)
M =	0.07	0.00	0.01	0.00	0.91	0.04	0.10	0.00	(62)
	0.00	0.06	0.01	0.00	0.01	0.84	0.14	0.00	
	0.00	0.01	0.05	0.00	0.06	0.08	0.67	0.00	
	0.00	0.00	0.00	0.07	0.00	0.02	0.07	0.98	

In the  $E_{cm}$  region of 4.0 to 4.4 GeV, the matrix of misidentification probabilities M has the following numerical elements:

	0.87	0,04	0.11	0.00	0.02	0.00	0.002	0.00	
	0.01	0.80	0.15	0.00	0.00	0.02	0.003	0.00	
	0.05	0.07	0.60	0.00	0.00	0.00	0.013	0.00	
м =	0.00	0.02	0.07	0.93	0.00	0.00	0.002	0.02	(63)
	0.07	0.00	0.01	0.00	0.91	0.04	0.12	0.00	
	0.00	0.06	0.01	0.00	0.01	0.84	0,15	0.00	
	0.00	0.01	0.04	0.00	0.06	0.08	0.63	0.00	
	0.00	0.00	0.01	0.07	0.00	0.02	0.08	0.9 <u>8</u>	

In the  $E_{cm}$  region of 4.4 to 6.4 GeV, the matrix of misidentification probabilities M has the following numerical elements:

	0.87	0.04	0.13	0.00	0.02	0.00	0.003	0.00	
	0.01	0.80	0.16	0.00	0.00	0.02	0.003	0.00	
	0.05	0.07	0.57	0.00	0.00	0.00	0.012	0.00	
	0.00	0.02	0.07	0.93	0.00	0.00	0.002	0.02	(64)
M =	0.07	0.00	0.01	0.00	0.91	0.04	0.14	0.00	
	0.00	0.06	0.01	0.00	0.01	0.84	0.16	0.00	
	0.00	0.01	0.04	0.00	0.06	0.08	0.60	0.00	:
	0.00	0.00	0.01	0.07	0.00	0.02	0.08	0.98	

In the E<sub>cm</sub> region of 6.4 to 7.4 GeV, the matrix of misidentification probabilities M has the following numerical elements:

0.87	0.04	0.17	0.00	0.02	0.00	0.0035	0.00	
0.01	0.80	0.17	0.00	0.00	0.02	0.0035	0.00	
0.05	0.07	0.52	0.00	0.00	0.00	0.011	0.00	
0.00	0.02	0.07	0.93	0.00	0.00	0.002	0.02	
0.07	0.00	0.01	0.00	0.91	0.04	0.175	0.00	(65)
0.00	0.06	0.01	0.00	0.01	0.84	0.175	0.00	
0.00	0.01	0.04	0.00	0.06	0.08	0.55	0.00	
0.00	0.00	0.01	0.07	0.00	0.02	0.08	0.98	
	0.87 0.01 0.05 0.00 0.07 0.00 0.00 0.00	0.87 0.04 0.01 0.80 0.05 0.07 0.00 0.02 0.07 0.00 0.00 0.06 0.00 0.01 0.00 0.00	0.87       0.04       0.17         0.01       0.80       0.17         0.05       0.07       0.52         0.00       0.02       0.07         0.07       0.00       0.01         0.00       0.06       0.01         0.00       0.06       0.01         0.00       0.01       0.04         0.00       0.01       0.04	0.87         0.04         0.17         0.00           0.01         0.80         0.17         0.00           0.05         0.07         0.52         0.00           0.00         0.02         0.07         0.93           0.07         0.00         0.01         0.00           0.00         0.06         0.01         0.00           0.00         0.06         0.01         0.00           0.00         0.01         0.00         0.00	0.87         0.04         0.17         0.00         0.02           0.01         0.80         0.17         0.00         0.00           0.05         0.07         0.52         0.00         0.00           0.00         0.02         0.07         0.93         0.00           0.07         0.00         0.01         0.00         0.91           0.00         0.06         0.01         0.00         0.01           0.00         0.01         0.00         0.01         0.00	0.87         0.04         0.17         0.00         0.02         0.00           0.01         0.80         0.17         0.00         0.09         0.02           0.05         0.07         0.52         0.00         0.00         0.00           0.00         0.02         0.07         0.93         0.00         0.00           0.07         0.00         0.01         0.00         0.91         0.04           0.00         0.06         0.01         0.00         0.01         0.84           0.00         0.01         0.04         0.00         0.08         0.08           0.00         0.00         0.01         0.07         0.00         0.02	0.87         0.04         0.17         0.00         0.02         0.00         0.0035           0.01         0.80         0.17         0.00         0.00         0.02         0.0035           0.05         0.07         0.52         0.00         0.00         0.00         0.011           0.00         0.02         0.07         0.93         0.00         0.00         0.012           0.07         0.02         0.07         0.93         0.00         0.00         0.002           0.07         0.00         0.01         0.00         0.91         0.04         0.175           0.00         0.06         0.01         0.00         0.01         0.84         0.175           0.00         0.01         0.00         0.06         0.08         0.55           0.00         0.00         0.01         0.07         0.00         0.02         0.08	0.87         0.04         0.17         0.00         0.02         0.00         0.0035         0.00           0.01         0.80         0.17         0.00         0.00         0.02         0.0035         0.00           0.05         0.07         0.52         0.00         0.00         0.00         0.011         0.00           0.00         0.02         0.07         0.93         0.00         0.00         0.002         0.02           0.00         0.02         0.07         0.93         0.00         0.00         0.002         0.02           0.07         0.00         0.01         0.00         0.91         0.04         0.175         0.00           0.00         0.06         0.01         0.00         0.01         0.84         0.175         0.00           0.00         0.01         0.04         0.00         0.06         0.08         0.55         0.00           0.00         0.00         0.01         0.07         0.00         0.02         0.08         0.98

112

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