PROC. 19th INT. CONF. HIGH ENERGY PHYSICS
TOKYO, 1978

P4 e⁺e~ Annihilation

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§1. Introduction

In principle this talk is supposed to review all the work that has been done in e⁺e~ annihilation in the past year or two. It won't for two reasons. First, in the next talk on particle spectroscopy, Giinter Fliïgge will cover recent work on charmonium, F mesons, the *Y* family, and related studies of jet structure at high energy. Second, even eliminating these topics, there is too much to cover in the time alloted. Thus, I have decided to break this talk into two segments. The first will briefly cover three topics: the status of resonances below 3 GeV, total cross sections ,and inclusive D spectra at high energy. The second segment, comprising the bulk of the talk, will be a comprehensive review of the properties of the ***T*** lepton.

There are several reasons for singling out the ***T*** for a detailed review at this time. First, it is one of only three charged leptons of which we have any knowledge. Clearly, our conception of the elementary particles and their interactions depends critically on the properties of this particle. Second, new results from five experiments have been presented to this conference or have become available in the past few months. And third, because of these results, there is now appearing a rather clear picture of the r as a sequential lepton. It thus appears to be an opportune time for this review.

§IL Resonances below 3 GeV

Isospin 1 resonances will appear in states with even numbers of pions. Data for e⁺e~ -» 4^ and 27r⁺2^° are shown in Fig. I.[1-5] In the 4;r⁺ state there is a broad enhancement centered around 1550 MeV/c². The 2^-⁺2^° cross sections are similar to those for 4^, but perhaps less peaked. The experimenters have made a variety of fits to the hypotheses that one or two resonances are present in these data,[1,2] but they should not be taken too seriously given the current statistical precision.

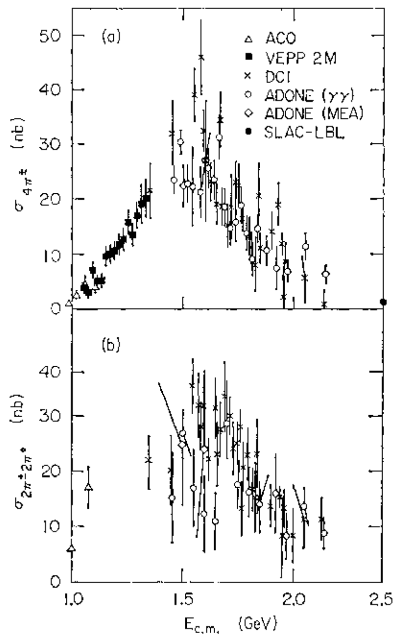


Fig. 1. Cross sections for the production of (a) 4TT⁺ and (b) *In*!*°* final states.

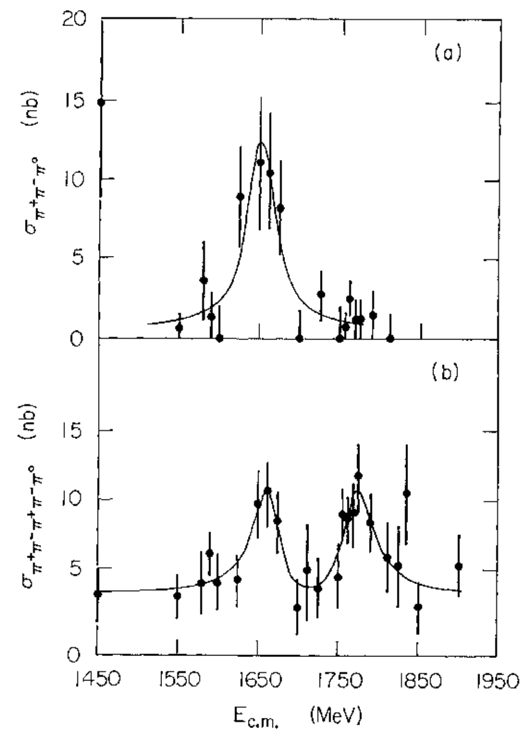


Fig. 2. Cross sections for the production of (a) ***I^ÎT°*** and (b) 4^° final states measured at DCI.[2]

The situation for isospin 0 resonances is somewhat clearer. The DCI experiment has seen evidence for a 40 MeV/c^2 wide resonance near 1660 MeV/c^2 in 3π and 5π states and a 50 MeV/c^2 wide resonance near 1770 MeV/c^2 in the 5π state.[1] These are shown in Fig. 2. The two peaks near 1660 MeV/c^2 each have a statistical significance greater than 3 standard deviations, and the peak near 1770 MeV/c^2 has a significance of about 5 standard deviations. These enhancements are narrower than one might expect for ρ' states.

Last year at the Hamburg conference, groups from ADONE presented evidence for three narrow resonances around 2130, 1820, and 1500 MeV/c^2.[6] There is no new information on the two higher mass resonances, but the region around 1500 MeV/c^2 has been restudied. Figure 3(a) shows new data from the $\gamma\gamma$ group

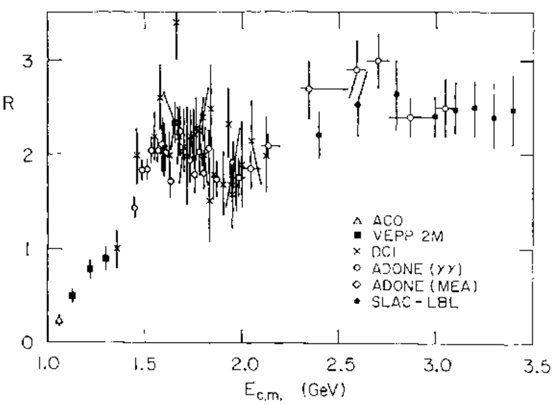


Fig. 4. R versus energy.

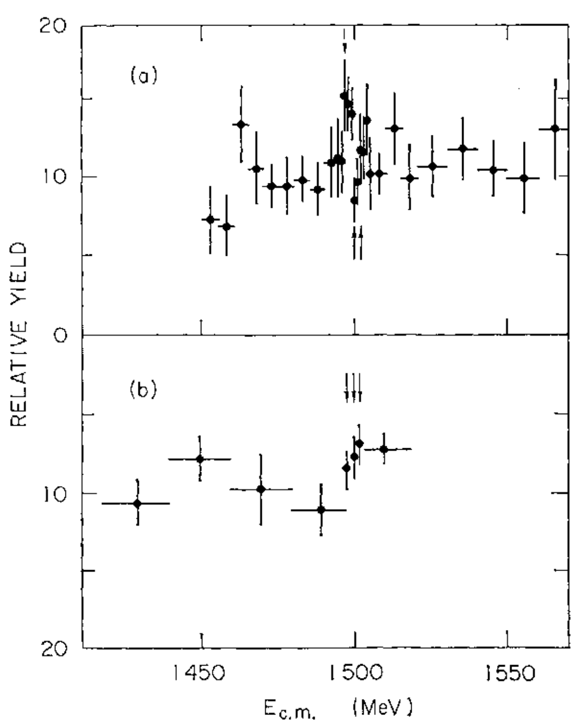


Fig. 3. Relative total cross sections versus energy near 1500 MeV measured by the $\gamma\gamma$ group at ADONE.[2] (b) shows higher statistics data taken to study possible structure seen in (a). The arrows indicate corresponding points.

which shows some weak evidence for an enhancement in this region.[2] In order to study this further a higher statistics run was performed on the three data points indicated by arrows. The results, shown in Fig. 3(b), do not show any evidence for the enhancement.

§III. Total Cross Sections

At this conference we have several new measurements of the ratio, R, of the total hadronic cross section to the muon pair production cross section. Figure 4 shows the lower energy data.[1,2,4,7,8] The results from

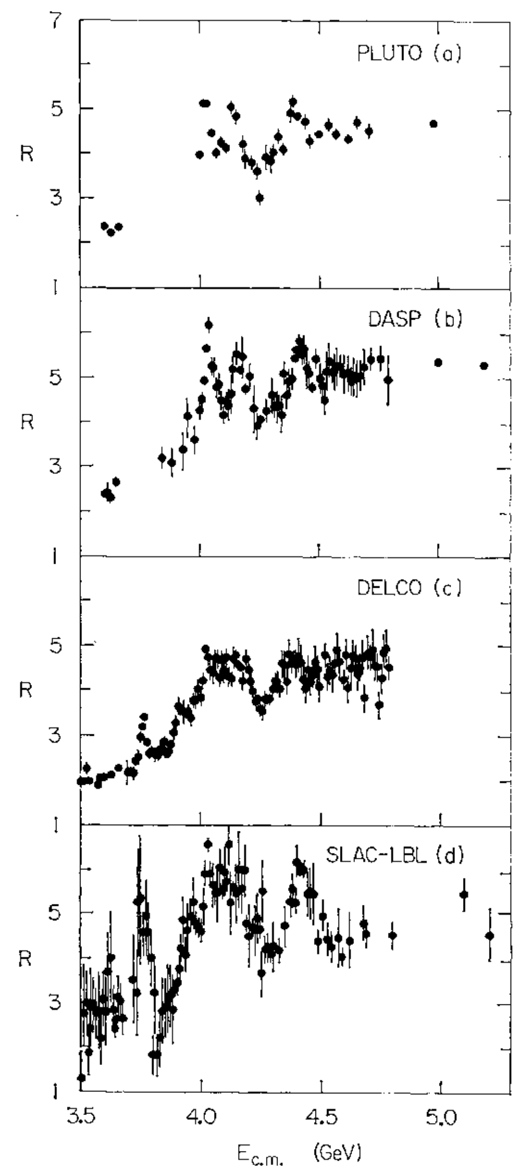


Fig. 5. R versus energy. The R values have been radiatively corrected in (a), (b), and (d), but not in (c). τ pair production is included in R.

DCI and ADONE agree well and it is interesting to note that the scaling value of approximately 2 sets in as low as 1.5 GeV.

The values of R around the threshold region for charmed particle production from four experiments are shown in Fig. 5.[9~12] These values of R include the contribution of r pair production. The DELCO results are presented without any radiative corrections; the other three experiments have made an attempt to correct for radaitive effects. We will return to this thorny problem shortly.

There is rather good agreement among the experiments for the general structure of the cross sections: there is a resonance-like peak at 3.77 GeV (<p")$_9$ a shoulder at 3.95 GeV, a peak at 4.05 GeV, a broad dip near 4.25 GeV, and a peak in the vicinity of 4.4 GeV. There is, however, some disagreement over details of the structure. For example there is a factor of 1.9 difference in the (p^M leptonic width measured by the DELCO[13] and lead glass wall (LGW) experiments.[14] The main disagreement between experiments on the existence of structure is the extent to which there is a dip at 4.10 GeV. The PLUTO and DASP results show a deep dip, while the DELCO and SLAC-LBL results show little evidence for one.

The four experiments agree surprisingly well on the general level of R. For example at the highest energy at which all of the experiments have reported measurements, 4.7 GeV, the values of R range from only 4.5 (PLUTO) to 5.0 (DASP) in spite of the fact that all the experiments have systematic uncertainties of around 15%.

The most vesing problem in these measurements is that of radiative corrections. Radiative effects always smooth out structure. Thus the application of corrections for radiative effects will always make observed peaks higher and observed dips deeper. One cannot apply radiative corrections on a point to point basis because this would greatly enhance fluctuations. In practice one has to have a perception of what structure exists before one can apply the corrections. If two experiments perceive different structure in their raw data, they will greatly enhance the difference in applying the corrections. A comparison of the SLAC-LBL and DASP data provides a good example. The two sets of data agree quite well everywhere except near 4.10 GeV where they apparently disagree by many standard deviations. Although I have not seen the raw DASP data, I am fairly sure that any disagreement in the raw data is within reasonable bounds of statistical uncertainty. Even though radiative corrections are slightly apparatus dependent, it would be very useful for experimenters to publish their data both with and without these corrections.

§IV. Inclusive D Meson Spectra at High Energy

The measurement of D meson energy spectra above the charmonium resonance region is important both because it is useful for predicting or unfolding secondary spectra from D decays and because it is interesting in its own right. There has recently been considerable theoretical speculation on how heavy quarks fragment into hadrons, and whether in particular the hadron containing the heavy quark would be unusually energetic.[15]

A measurement of this type by the SLAC-LBL and LGW experiments has been presented to this conference at an average energy of 7 GeV.[16,17] The technique is simply to plot and K^n^n* invariant mass spectra in several momentum bins and to extract the D

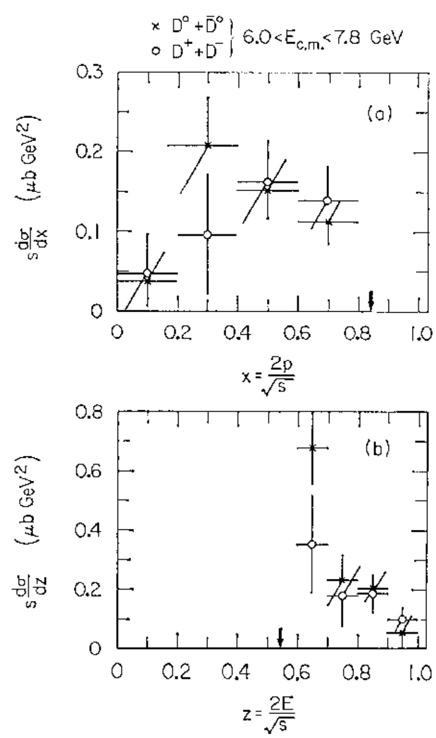


Fig. 6. Inclusive **D** production at 7 GeV versus (a) $x=2_{Pr}/E_{c.m.}$ and (b) z=2£$_D$/£'$_{c.m.}$.[16,17]

cross sections by fitting to a D peak plus background. Even at 7 GeV the D mass severely restricts the kinematic range over which this measurement can be made. Using the variable x=2p$_D$/2?$_{Q.m.}$, the allowed kinematic range is 0<x<0.84; for *z=2E$_B$/E$_{Cmmm9}$* the allowed range is 0.54<z<l. The spectra in these two variables are shown in Fig. 6. Figure 7 shows a comparison between D spectra and *n* and K spectra. Within the limited kinematic range available the D spectra

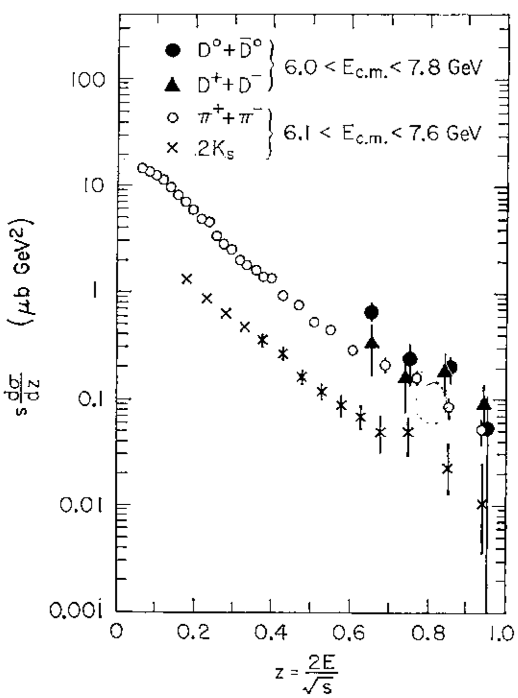


Fig. 7. Inclusive D production at 7 (SeV versus z compared to inclusive *x* and K production.

seem to be consistent with having the same slope as those of other mesons. The data give good fits to either

$$(d\sigma/dz)\propto(1/z)(1-z)^{(0.7\pm0.4)}$$

or

$$(d\sigma/dz)\propto e^{-(5.5\pm1.5)z}.$$

§V. Review of r Properties

A. History

Although this talk will not be organized in a chronological manner, I think it is useful to spend a minute or two putting the present situation into its historical perspective.

The history of the *r* began in 1975 with the observation by the SLAC-LBL group of 24 events which contained an electron and a muon but no other visible charged or neutral particles.[18] These events could not be explained by any known processes. Possible hypotheses which could explain these data included the decay of a new lepton or a weakly-decaying spin one boson.

The SLAC-LBL group collected additional data and studied the momentum spectrum of the leptons and the presence or absence of other particles in these events. It concluded that the lepton momentum spectrum was characteristic of a three-body decay and that, by elimination, the missing particles had to be neutrinos. In a paper published in 1976, the SLAC-LBL group stated.

> 'The simplest hypothesis compatible with all the data is that these events come from the production of a pair of heavy leptons.. .[19]

This was the state of the *v* at the last conference in this series. All of the evidence for a new lepton came from a single experiment and one that admittedly had poor lepton identification. Independent confirmation was badly needed. It came during the following year from the PLUTO[20,21] and DASP[22] experiments.

It is clear that at this conference we are entering a new stage in the history of the r. Its existence and general identification are accepted and we are beginning the detailed measurements of its properties.

It is in this spirit that I have prepared this review. In the next section we shall review the measurements of *r* branching fractions, first the general modes, then a more detailed look at the semi-hadronic modes, and finally, a review of upper limits for rare modes. In sections C through G we shall briefly review measurements of the ***T*** mass, the ***T*** spin, the *v* lifetime, the ***T~V$_r$*** coupling and the *v$_x$* mass. We shall conclude in section H with a discussion of the type of lepton the *r* could be.

B. Branching fractions

Figure 8 illustrates the three possible *r* decay modes in the standard model. In each case the ***T*** decays to its own neutrino, *v$_r$*, and the charged weak current, which can materialize as an ev$_e$, a *pû$_{p9}$* or a dû pair. The du quark pair (or more precisely the *d'u* pair, where *d'* = *d* cos$^{2'}$6$_c$'*rs* sin^2#$_c$) forms a hadronic system such as a charged **TT,** *p*, or *A$_{lt}$* There are three general observations that we can make from Fig. 8:

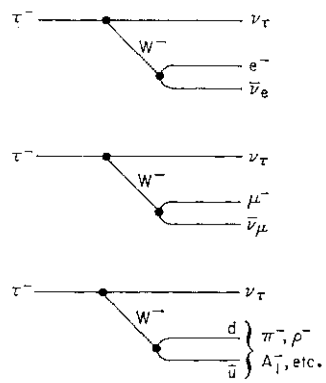


Fig. 8. τ decay modes.

(1) Each of the diagrams has equal weight since all of the couplings to the weak current are equal, with the proviso that the last diagram stands for three diagrams corresponding to the three colors of quarks. Thus, there are five equivalent diagrams and so the electronic branching fraction should be 20%. QCD corrections give an enhancement to the semihadronic final states and reduce the prediction for the electronic branching fraction to 18 %.[23]

(2) Many of the branching fractions for the semi-hadronic modes are precisely predicted. For example, the coupling of the the *ju* and the 7T to the weak current is known from the measurements of their lifetimes. Thus, the ratio of branching fractions for *T->KV* to that for ***T***-**jbtvv* is precisely predicted. We shall return to a discussion of the predictions for the semi-hadronic modes below.

(3) Most *v* decays will contain only one charged particle. Clearly the decays to e's, *ju's* 7r's, and *p's* contain only one charged particle, and it will turn out that about half of the semi-hadronic modes contain only one charged particle. Thus production will be most prominent in events with only two charged particles.

Table I. Experiments which have measured ***T***⁺***T***~ production, the method of electron identification (if relevant), and the modes measured.

Experiment	Institutions	Laboratory	e⁻ ident.	Modes eμ	ee	μμ	ex	μx
SLAC-LBL	LBL SLAC	SPEAR (West pit)	Lead-scintillation counters	V	V	V		V
PLUTO	DESY Hamburg Siegen Wuppertal	DORIS	Lead-proportional chambers	V				V
DASP	Aachen DESY Hamburg München Tokyo	DORIS	Cerenkov counters (ex) or lead proportional chambers (eμ)	V			V	V
LGW	Hawaii LBL Northwestern SLAC	SPEAR (West pit)	Lead-glass counters	V			V	
MPP	Maryland Pavia princeton	SPEAR (East pit)	—					V
Iron Ball	Colorado Pennsylvania Wisconsin	SPEAR (East pit)	—			V		
DELCO	Irvine Los Angeles Stanford Stony Brook	SPEAR (East pit)	Cerenkov counters	V			V	
DESY-Heidelberg	DESY Heidelberg	DORIS	NaI and lead-glass counters					
Mark II	LBL SLAC	SPEAR (West pit)	Lead-liquid argon counters					

Table II. Measurements of B_e, By, B_{1h}, and B_{3h}.

Mode	Measurement	Experiment	Result	Reference
eμ	$\sqrt{B_e B_\mu}$	SLAC-LBL	.186±.030	24
eμ	$\sqrt{B_e B_\mu}$	PLUTO	.145±.040	20
eμ	$\sqrt{B_e B_\mu}$	DASP	.182±.031	25
eμ	$\sqrt{B_e B_\mu}$	LGW	.224±.055	26
eμ	$\sqrt{B_e B_\mu}$	DELCO	.183±.039	11
ee	B_e/B_μ	SLAC-LBL	1.12±0.48	27
$\mu\mu$	B_μ/B_e	SLAC-LBL	1.40±0.48	27
$\mu\mu$	B_μ	Iron Ball	.22± .08	28
ex	$B_e(B_\mu+B_{1h})$	DASP	.086±.012	25
ex	$B_e(B_\mu+B_{1h})$	LGW	.151±.064	26
ex	$B_e(B_\mu+B_{1h})$	DELCO	.084±.013	29
μx	$B_\mu(1-B_{3h})$	SLAC-LBL	.149±.034	24
μx	$B_\mu(1-B_{3h})$	PLUTO	.109±.025	21
μx	$B_\mu(1-B_{3h})$	MPP	.170±.085	30
μx	B_μ/B_e	DASP	.92 ±.32	25
e-any	B_{3h}	DELCO	.32 ±.05	29, 34
e-any	$B_e B_{3h}$	DELCO	.045±.010	33, 34
μ-any	B_{3h}	PLUTO	.30 ±.12	21

General modes

From the preceding discussion it is clear that T^+T^- production can be most easily measured by studying e^+e^- annihilation events with two charged particles in which at least one is a lepton. There are five possibilities: *e/u*, ee, *fjifi*, ex, and //x, where x stands for any charged particle. Seven experiments have measured one or more of these modes,[20-30] and two other experiments have measured other modes or properties.[31,32] Table I gives a list of these experiments and the modes which each measured.

From these measurements we want to derive the branching fractions for r decay into evv (B_e), *juw* (*By*), one charged hadron plus neutrals (B_{1h}), and three or more charged hadrons plus neutrals (B_{3h}), subject to the constraint that the sum of these four modes is unity. Table II gives the results of the 15 measurements listed in Table I. An attempt has been made here to determine precisely the quantity that each experiment measured. In general, experiments measure products or combinations of products of these four basic branching fractions, and then use either theoretical assumptions or other experimental measurements to derive the branching fractions quoted in their papers. Thus the values quoted in Table II are derived from the results given in the reference papers, but in some cases may not be explicitly found there. Table II also includes three measurements of $2?_{3h}$ which were determined by studying the multiplicity accompanying a single lepton in regions in which charmed particle production is unimportant.[21,29,33]

The results of constrained fits to the 18 measurements in Table II are given in Table III. One fit has been done leaving B_e and *By* free and the other has constrained .5^=0.973 B_e, its theoretical value. Both fits are extremely good and, in fact, all 18 measurements agree with the fit results within one standard deviation of the experimental errors. Although no single experiment has done a particularly sensitive job of testing *c-ju* universality in *T* decays, the result of all measurements taken together provides a reasonably stringent limit on its violation. Also, it is impressive that there is excellent agreement between the theoretical prediction for the electronic mode, 18%, and the results of the fits.

Table III. Results of constrained fits to the measurements listed in Table II.

	B_e and B_μ free	B_μ=0.973 B_e
B_e (%)	16.5 ±1.5	17.5±1.2
B_μ (%)	18.6 ±1.9	17.1±1.2
B_{1h} (%)	34.3 ±4.2	35.0±4.0
B_{3h} (%)	30.6 ±3.0	30.4±2.9
B_μ/B_e	1.13±0.16	

Semi-hadronic modes

Many details of the semi-hadronic decays are predicted in the standard model.[35,36] As we mentioned previously, the ratio between the leptonic decays and the %v mode is precisely predicted from the pion lifetime. The vector decays, which are decays to even numbers of pions plus a neutrino, are precisely predicted from measurements of e+e~ annihilation *via* the conserved vector current hypothesis[37] The decay to *pv* is the largest component of this class. For the axial-vector decays, the A_1 plays the same role as the *p* does for vector decays. For this reason, it is hoped that *z* decays will provide a convenient way to study the A_1, which has proved so difficult to isolate in hadronic interactions.[38] The A_1 *v* branching fraction can be calculated from the *pv* branching fraction with the aid of Weinberg's sum rules.[39] r decays involving kaons will be suppressed by tan $^2\theta_c$ in the standard model. A summary of these predictions is given in Table IV under the assumption that B_e=B^ 18%.

The *pv* decay mode has been measured by the DASP group[40] to have a branching fraction of (24±9)% in good agreement with the theoretical expectation of 20 % from Table IV.

Table IV. Predictions for **r** branching fractions under the assumption that B_e=Bfi=.IS.

Mode	Branching fraction (%)	Input
$e\nu\nu$	18	Measurement
$\mu\nu\nu$	18	Measurement
$\pi^-\nu$	10	π decay
$\rho^-\nu$	20	CVC+e^+e^- annihilation
$(4\pi)^-\nu$	10	CVC+e^+e^- annihilation
$A_1\nu$	9	Weinberg sum rules
$(K+n\pi)^-\nu$	4	tan $^2\theta_C$
(3 or $5\pi)^-\nu$	11	Remainder

The Mark II experiment has also presented preliminary data on the *pv* decay mode to this conference.[32] Although no quantitative branching fraction was quoted, it was stated that the result was consistent with the expected theoretical result.

The DASP group has studied ***T*** decays to strange particles by measuring the fraction of ex events in which the x is a kaon. The result is (7±6) % in agreement with the prediction in Table IV.

We shall now review in more detail the measurements on two interesting classes of semi-hadronic decay modes: *izv* and *(3TT)V.*

The TTV mode

Last summer at the Hamburg Photon-Lepton Sympsoium, the DASP group reported that the r-»7rv branching fraction was substantially smaller than expected.[40] This was rather surprising since, as we have already discussed, the ***Ttv*** mode is completely predicted and a failure of this prediction would imply, at the least, that different weak currents were important in ***T*** and ***xr*** decays. The DASP group searched for a high momentum pion (> 1 GeV/c) with an electron or any charged particle and no detected photons. Nine events were expected but only four were seen. When any charged particle plus a pion was required only 17 events were found and 34 were expected. Above 4.52 GeV center-of-mass energy only four events were found and 13 were expected.[41]

As of this conference four experiments have repeated the DASP measurement in either the **e7r** or *xx* modes.[32,42-44] All four experiments are in good agreement with the theroetical prediction. In each case the pion momentum spectrum is close to constant, which is expected for the *v-+m>* decay mode but would be rather unlikely for possible background sources. Table V summarizes the results of these experiments. The weighted average of these four measurements is a branching fraction of (8.3±1.4)% in good agreement with the theoretical prediction. The ***T-*KV*** mode requires more detailed study, but given the results of these experiments, there is no longer good reason to suspect that it is anomalous.

(3TC)V and (4TT)V modes

The PLUTO[45,46] and SLAC-LBL[47] groups have studied r decays to three charged pions plus a neutrino. These decays are of particular interest since the long-sought A_1 meson is expected to be prominent in the three pion mass spectrum.

The SLAC-LBL group studied events with a muon, three charged pions, and any number of photons. The three pion mass spectrum after background subtractions is shown in Fig. 9 for cases in which no photons, one or two photons, and more than two photons are observed. In the first two cases there is a

Table Y. Results on the r-±%v decay mode. The first error is statistical, the second systematic.

Experiment	Mode	Events	Background	$B(\tau\rightarrow\pi\nu)$(%)	Reference
SLAC-LBL	$x\pi$	~200	~70	9.3±1.0±3.8	42
PLUTO	$x\pi$	32	9	9.0±2.9±2.5	43
DELCO	$e\pi$	18	7	8.0±3.2±1.3	44
Mark II	$x\pi$	142	46	8.0±1.1±1.5	32
	$e\pi$	27	10	8.2±2.0±1.5	
Average				8.3±1.4	

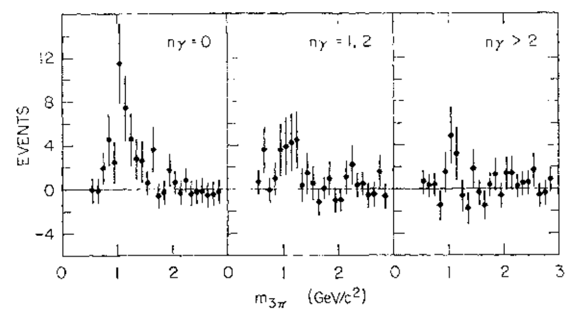


Fig. 9. Invariant mass distributions of three pions in events in Which they are detected along with a muon and zero, one or two, or more than two photons. The distributions have been corrected for hadron misidentification as a muon. The data are from the SLAC-LBL and LGW experiments.[47]

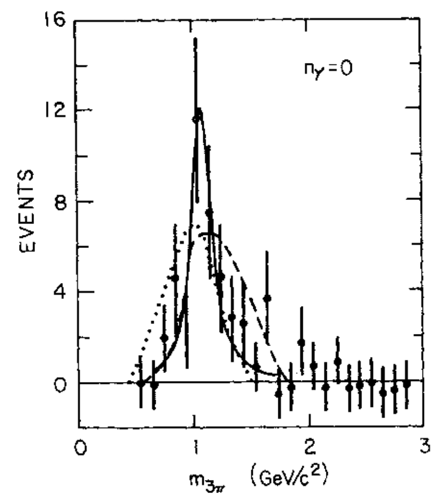


Fig. 11. Data from Fig. 9(a) with fits to different hypotheses. The dotted line represents r-» 7i7iK~7i°v-decays, the dashed line represents non-resonant r->7r7r7r~y decays, and the solid line represents T->AiV decays where the A_1 has a mass of 1.1 GeV/c² and width of 200 MeV/c².

significant signal in the vicinity of 1.1 GeV/c². The momentum spectra of the muon and the three charged pions in this mass region agree with hypothesis of pair production, as seen in Fig. 10. Figure 11 shows fits to the three pion mass spectrum with no detected photons under three hypotheses: (a) that all the events are due to T~+K°ir7T~7r°v, where the K° is not detected, (b) that all the events are due to T-*p°nv, where the ^°TT is non-resonant, and (c) that all the events are due to T-*A,I>-+H:7CX~V. Fits to the first two hypotheses have only a few percent confidence level but cannot be excluded. The resonance hypothesis is a good fit with Ax mass of 1.1 GeV/c² and full width of 200 MeV/c².

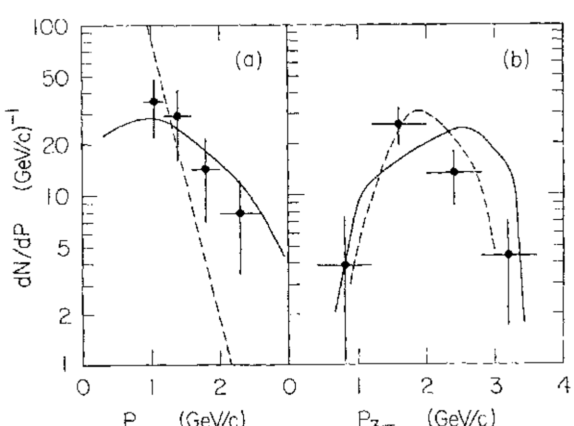


Fig. 10. (a) Momentum distribution of muons in events in the .95<m,*<1.25 GeV/c² region of Fig. 9(a) and (b). The solid and dashed curves are the expected spectra from é decays and charmed particle decyas. (b) Momentum distribution of the three pion system in these events. The solid and dashed curves are the spectra expected for r~>3nv and r~>47ri; decays.

The SLAC-LBL group obtains an (18±6.5) % branching fraction for r-*7r7r7r~+n7r°y. By using the number of observed photons, in principle it is possible to unfold this branching fraction for the number of ;r's produced. In practice the statistical accuracy is rather poor. The results are (7±5) % for T-^TZ^TZ^TZ^V and (11 ±7)% for T-*%+IZ*%-%%. All these results are consistent with the theoretical predictions given in Table IV.

The PLUTO group has studied events with an electron or muon, three charged pions, and no photons. Since PLUTO has more efficient photon detection than the SLAC-LBL detector, the background from the 4nv decay to the *3TTV* signal is small. This has allowed the PLUTO group to go beyond the SLAC-LBL analysis in two significant aspects. First, a study of dipion masses showed that the entire signal was consistent with two of the pions forming a ***p°***. The higher mass dipion combination for each event is shown ifr Fig. 12. Second, an analysis of the three pion Dalitz plot has shown that the three pion state is consistent with the expected spin-parity assignment of 1⁺, but not 0~ or 1". The normalized distance to the Dalitz plot boundary is shown in Fig. 13. The axial-vector hypothesis fits the data with a 10% confidence level. The hypotheses that the 3rc system is a pure pseudoscalar or vector state are excluded at the

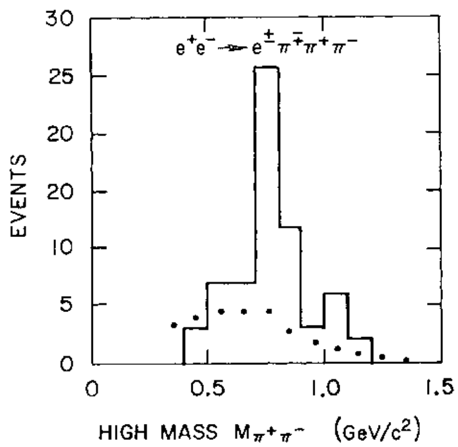


Fig. 12. Invariant mass of the higher mass *TT+TT"* pair from events with a lepton and three charged detected which are compatible with ***T⁺T~*** decays. The dotted curve represents an estimate of the background. The data are from the PLUTO experiment.[45146]

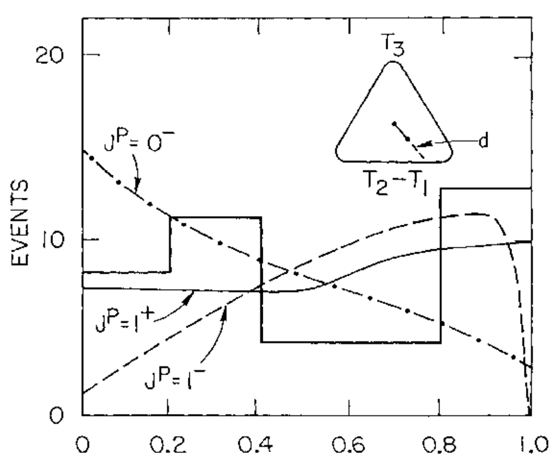


Fig. 13. The normalized distance to the boundary of the *3n* Dalitz plot for *p°iz* data described in Fig. 12. The curves show the expected distributions for 0~, 1~, and 1⁺ spin-parity 3^ states.

0.01 % and 0.3% confidence levels. A vector 3**TT** system would require second class currents.

The 3**TT** mass spectrum from the PLUTO experiment is shown in Fig. 14 along with a

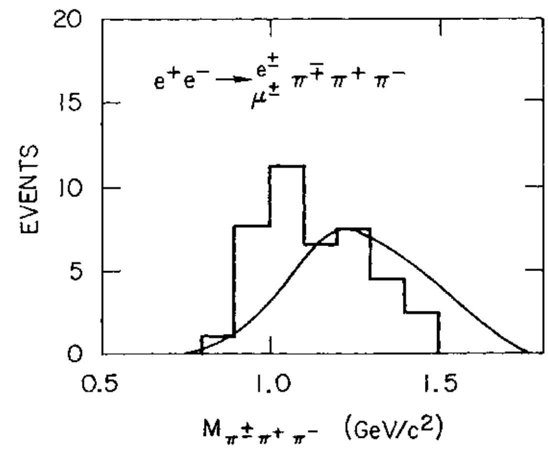


Fig. 14. Invariant mass distribution of *P°K* combinations for events described in Fig. 12. The curve repesents a non-resonant *p°n* spectrum from *r* decay.

curve representing ***pit*** non-resonant phase space. These appears to be an enhancement near 1.0 GeV over the phase space curve. The branching fraction for ***T->p7iv*** from the PLUTO experiment is (10.4±2.4)% where the result includes both the ***p°7t*** and ***p+n°***. final states.

Finally, what can we say about the *A₁* given the results from these two experiments ? There are at least three statements which can be made without serious fear of contradiction:

(1) It is significant that both experiments see an enhancement near 1.1 GeV.

(2) The present data are statistically insufficient to pin down the *A₁* parameters.

(3) In the future *r* decays will be crucial in understanding the *A₁*.

Rare decay modes

There have been numerous searches for r decay modes which should not exist in the standard model.[20,48149] There is no evidence for any of these modes and the upper limits are given in Table VI.

C. r *Mass*

DASP was the first experiment to use the energy dependence of the r production cross section to deduce a precise value for the r mass.[25] The result was 1807±20 MeV/c^2 and the data are shown in Fig. 15.

Table VI. Upper limits on rare r decay modes, stands for any charged particle and "7" stands for any charged lepton.

Mode	Experiment	Upper limit (%)	Confidence level (%)	Reference
3x	PLUTO	1.0	95	48
3l	SLAC–LBL	0.6	90	49
l+charged particles	PLUTO	4.0	90	20
l+ photons	PLUTO	12.0	90	20
$e^-+\gamma$	SLAC–LBL	2.6	90	49
$\mu^-+\gamma$	SLAC–LBL	1.3	90	49

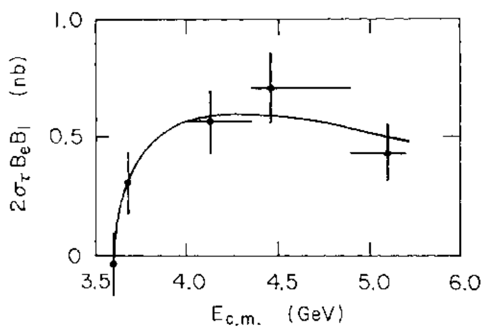


Fig. 15. Cross sections for ex events measured by DASP experiment. The curve is a fit to the production cross section for point-like spin 1/2 particles.

Later measurements by DESY-Heidelberg[31] and DELCO[11 29] are shown in Figs. 16 and 17,

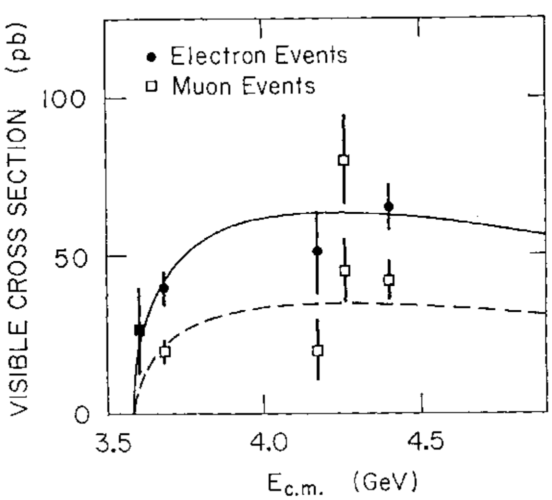


Fig. 16. Observed cross sections for ex and ^x events measured by the DESY-Heidelberg experiment. The curves are fits to the production cross sections for point-like spin 1/2 particles.

with results of 1790±I₀ and 1782i| MeV/c², respectively. The DELCO data beautifully delineate the r threshold by having points just above and just below it. The high precision of the DELCO mass determination is primarily due to the data point at 3,570 MeV which

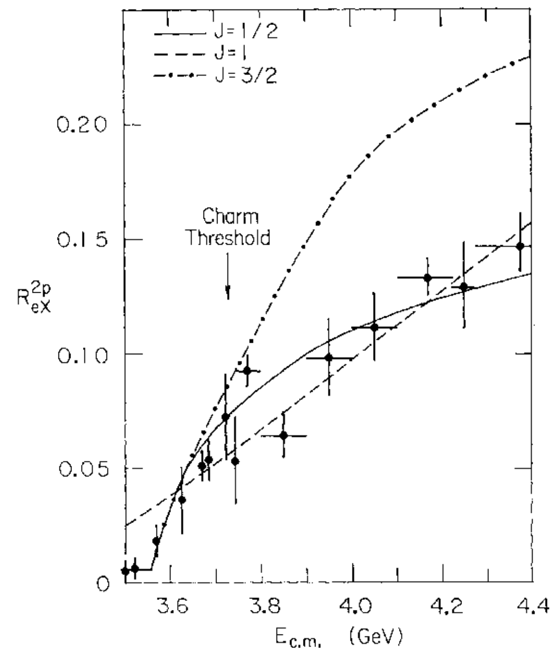


Fig. 17. The ratio of ex events to \i pair production as a function of center-of-mass energy. The solid curve is a best fit to the spin 1/2 r pair production cross section. The dashed and dot-dashed curves represent typical cross sections for spin 1 and spin 3/2 particle production. The data are from the DELCO experiment.[11]

observed 8 ex events with 1.6 expected from backgrounds. Although there is no reason to suspect this point, it is worth noting that if it were removed from the fit, the remaining data points would pull the r mass to \190tl MeV/c² as can be seen from the existence of a second minimum in the f versus mass plot, Fig. 18.

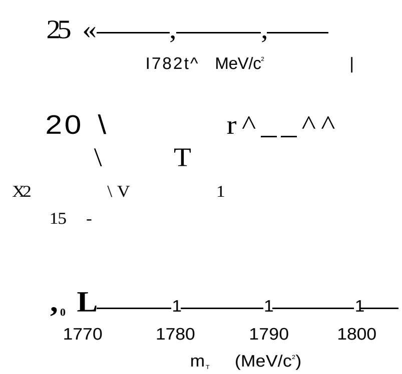


Fig. 18. x^2 f°' 17 degrees of freedom for the fit to the *T* mass from the data in Fig. 17.

D, *T* Spin

As long as we assume that the z does not have a form factor which varies rapidly over the range of a few GeV, all spin assignments except 1/2 are excluded. All integer spins will require a /3[3] threshold dependence and half-integer spins greater than 1/2 will lead to much too large a cross section above 4 GeV when normalized to fit the threshold region.[50] These points are illustrated in Fig. 17 by the spin 1 and 3/2 curves.

E. z Lifetime

The r lifetime has been studied by examining the closest distance of approach to the interaction region of leptons from z decays. The best upper limits are 3.5x10~[12] sec from the PLUTO experiment[46] and 3.0 X 1CT[12] sec from the DELCO experiment/[1] both at the 95% confidence level. For a full strength z-ν_x coupling to the weak current and assuming the ν_τ is massless, the z lifetime, r„ is given by

$$\tau_\tau = B_e(m_\mu/m_\tau)\tau_\mu = (2.8\pm0.2)\times10^{-13}\ \text{sec},$$

where the error is primarily from the uncertainty in the electronic branching fraction, B_e. Thus the z-ν_τ coupling has to be at least 9% of full strength.

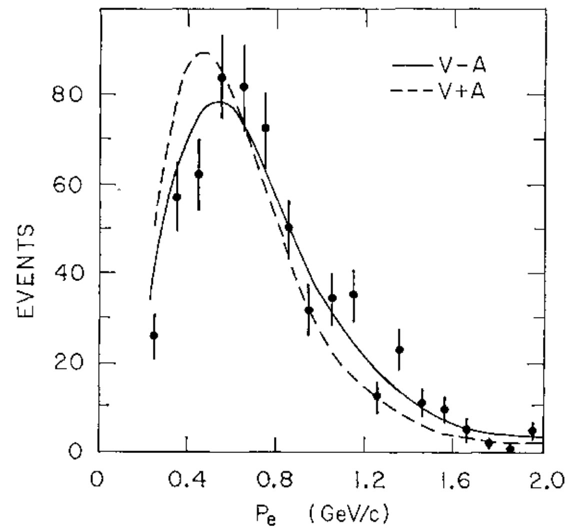
F. z-ν_τ Coupling

The lepton momentum spectrum can be used to determine the F, A structure of the z~ν_τ coupling. V— A gives the hardest spectrum, V+A gives the softest, and pure V or A is halfway in between. The PLUTO experiment favored V—A over V+A slightly.[21] The SLAC-LBL experiment strongly disfavored V+A, giving it a statistical confidence level of at most a few percent.[24]

The most conclusive data on the z-ν_τ coupling were reported to this conference by the DELCO experiment.[11] They have extracted a Michel parameter, p, of 0.83+0.19 from the electron momentum spectrum of ex events, shown in Fig. 19. The radiatively corrected Michel parameters for V—A is 0.53, for V+A is -0.15, and for either V or A is 0.91.[51] The confidence level for V— A is 4%, while the confidence level for V+A is infinitesimal. Thus the DELCO data completely exclude V+A and strongly disfavor pure V or A.

G. ν_τ Mass

If the ν_τ had a mass, it would soften the charged lepton momentum spectrum. All experimental measurements are consistent with a massless j^.[11,12,24,52] The upper limits on the ν_ν mass are given in Table VII.



Fig, 19. Electron momentum spectrum for ex events at energies between 3.57 and 7.4 GeV. The solid and dashed curves represent the spectra expected for V—A and V+A r-ν_ι couplings. The data are from the DELCO experiment.[11]

Table VII. Upper limits on ν_τ.

Experiment	Upper limit (MeV/c^2)	Confidence level (%)	Reference
SLAC–LBL	600	95	24
PLUTO	540	90	52
DELCO	250	95	11

Table VIII. Summary of selected **r** properties

Parameter	Experimental findings
Mass	1782^{+3}_{-4} MeV/c^2
Neutrino mass	<250 MeV/c^2 at 95% confidence level
Spin	1/2
Lifetime	$<3\pm10^{-12}$ sec
τ–ν_τ coupling	Consistent with V−A, V+A excluded
B_e	0.175±0.012 (assuming B_μ=.973 B_e)
B_μ/B_e	1.13±0.16

H. What Type of Lepton is the r?

All of the evidence, summarized in Table VIII, is consistent with the z being a sequential lepton decaying to its own massless neutrino with a V—A coupling.

One can ask, however, what other possibilities could exist.[53] The simplest case would be to have the r, but no ν_ν in an SU(2)xU(l) gauge theory. The z would then decay into a mixture of ν_e and An analysis of this case shows that it is excluded by several of the measured z properties. For example, the z would have to decay into 3 charged leptons at a rate an order of magnitude above the experimental upper limit,[54,55] and B_{μ}/B_{e} would have to be close to 0.5 or 2.0.[55]

Another possibility is that the v_x exists, but is more massive than the r. This is also excluded.[56] The argument is that the sum of couplings to p_e *and* must be greater than 0.09 of full strength from the *v* life-time measurement. But the coupling is limited to 0.025 by the absence of *r* production by *v* beams,[57] and the v_e coupling is limited to be less than 0.006 more than the v_e coupling by the *n^⁄uv/rr-^çv* ratio.[58]

Dropping the requirement of an SU(2)x U(l) gauge theory, one can ask more generally whether it is possible that the r" has the same lepton number as either the e~, e$^+$, or ; that is, whether it couples to the v_e, v_e, or *ûft.* The *r~* cannot have the lepton number of either the *ju~* or */u*$^+$ it would be produced in *v* interactions. The *t~* cannot have the lepton number of either the e$^+$ or //$^+$. If it did there would be two identical neutrinos in the final state and B_{μ}/B_{G} would be either .5 or 2.

The one possibility which cannot be excluded at present is that the *z~* has the same quantum number as the e". Detailed measurements of v_e interactions, possibly from beam dump or tagged decay experiments, may be able to address this question in the future.

Of course, there are many more possibilities than the simple ones we have discussed here, and, in general, one must simply compare the predictions of a given model to the range of parameters allowed by the data. It is remarkable, in the three years since the *r* discovery, how tight the constraints have become.

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P5a: Particle Spectroscopy, Experimental. I

Chairman : G. H, STAFFORD

Speaker: G. FLÙGGE

Scientific Secretaries: Y. SUMI
R. SUGAHARA

P5a': Particle Spectroscopy, Experimental. II

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P5b: Particle Spectroscopy, Theoretical

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(Tuesday, August 29, 1978; 9: 45-12: 30)