Istituto Nazionale di Fisica Nucleare
Sezione di Pavia

INFN/AE-76/10
29 Novembre 1976

G. Goggi : NEW STATES IN e^+e^- ANNIHILATION. -

(Rapporteur's talk at the 62[th] Meeting of the Italian Physical Society, Trento, September 1976).

1. - INTRODUCTION. -

The production of hadrons by e^+e^- annihilation proceeds mainly via a single time-like photon, which defines a state with the quantum numbers $J^{PC} = 1^{--}$ and all additive quantum numbers equal to zero. Consequently any particle coupled to the photon with the same quantum numbers can be observed as an enhancement in the total annihilation cross section when the energy in the e^+e^- system equals the mass of the state. The total hadronic cross section, wich up to QED terms is equivalent to the total annihilation cross section, is therefore a powerful means to study the coupling between the virtual photon and any elementary component of the hadronic current. In addition the possibility of defining precisely the energy of the e^+e^- allows a fine scan to be made across these hadronic components of the photon.

Fig. 1a shows the total hadronic cross section between 2.4 and 7.8 GeV ; it generally falls with increasing c.m. energy except in the 4 GeV region, where it exhibits a rather complex

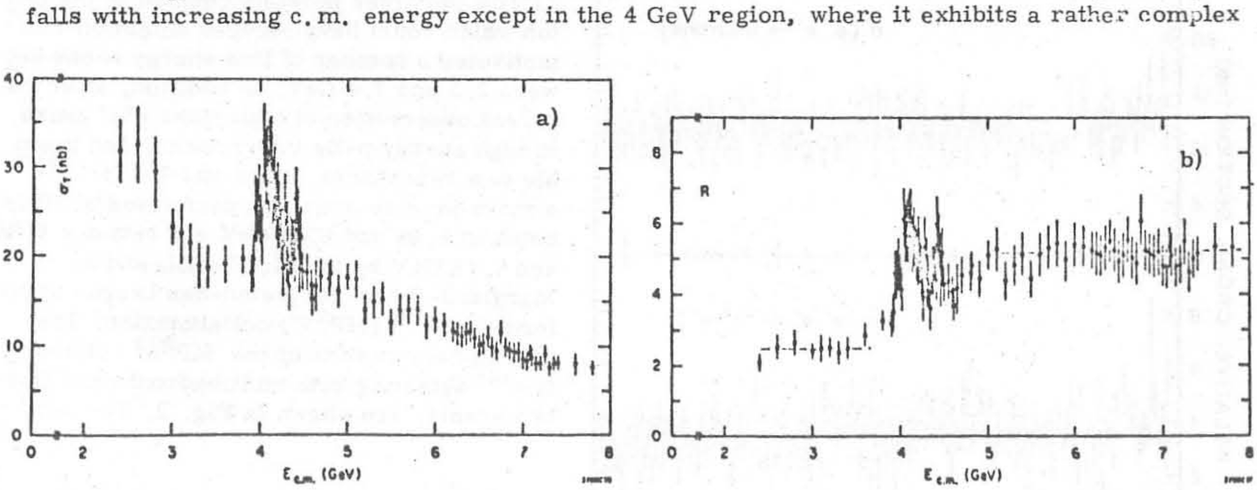


Fig. 1 - a) Total hadronic cross section vs. c.m. energy. Radiative tails of the ψ resonances have been subtracted. b) R versus c.m. energy.

structure. When the obvious dependence on the photon propagator is removed the quantity R is obtained, defined as the ratio of the total hadron cross section to the QED cross section for pointlike fermion production. This quantity, shown in Fig. 1b, not only represents a more general approach to the hadron-photon vertex structure function but is numerically related, in a wide class of models, to the details of the hadron structure :

$$R(W) \underset{W\to\infty}{\longrightarrow} \lambda \sum_i Q_i^2 , \qquad (1)$$

where W is the c.m. energy and Q_i the charge of the i-th quark; λ is a number which depends on the various structural parameters of the hadrons. The value of R(W) reflects then the sum of the squares of the charges of fundamental fermions at the energy W and R(W) becomes the basic measurement of hadron physics by revealing the number and the charges of their quark constituents.

The behaviour of R(W) in Fig. 1 is approximately constant below 3.5 GeV at a value of about 2.5, is again roughly constant above 5 GeV, but at a level approximately twice that of the lower energy scaling region and shows in between a very complicated transition region. On these grounds it is now customary to separate the physics of e^+e^- annihilation into an "old", a "threshold" and a "new" region. This is not only suggested by the behaviour of R, but also by the theoretical prejudice that around 3 to 4 GeV a new quark degree of freedom is being excited. The dramatic doubling of R through the transition region, close and probably related to the two enormous narrow ψ resonances, poses the challenging experimental question whether there are fundamentally new processes above 4 GeV and, if so, what distinguishes the "new" physics from the "old".

In the following, after discussing briefly the results of the searches for new narrow objects in the one-photon channel, I shall focus on the search for new states produced in e^+e^- annihilation in the transition region, both those possibly carrying a new quantum number and those without. I shall summarize results obtained at Adone, SPEAR and DORIS; a considerable fraction of these results has not been published and is therefore to be taken as preliminary.

2. - SEARCH FOR OTHER NARROW STATES. -

If ψ and ψ' are taken to be bound states of a new heavy quark carrying a new quantum number conserved by strong and electromagnetic interactions, the decays of these particles into ordinary hadrons are forbidden by the Zweig-Iizuka[1] rule, which explains the strongly suppressed hadronic widths. The search for other narrow particles possibly coupled to the photon which could have escaped detection has motivated a number of fine energy scans between 2.5 and 7.4 GeV. In addition, after the recent observation of high mass e^+e^- pairs in high energy p-Be interactions, and possible new resonances at 6.0 and 7.2 GeV[2], a more precise scan was performed at SPEAR between 5.65 and 6.64 GeV and between 6.95 and 7.45 GeV by the SLAC-LBL and by the Maryland-Pavia-Princeton-San Diego-Stanford-SLAC[3] (MP^2S^3) collaboration. The preliminary results of the MP^2S^3 collaboration[4] detecting both multihadronic and Bhabha events, are shown in Fig. 2. The data

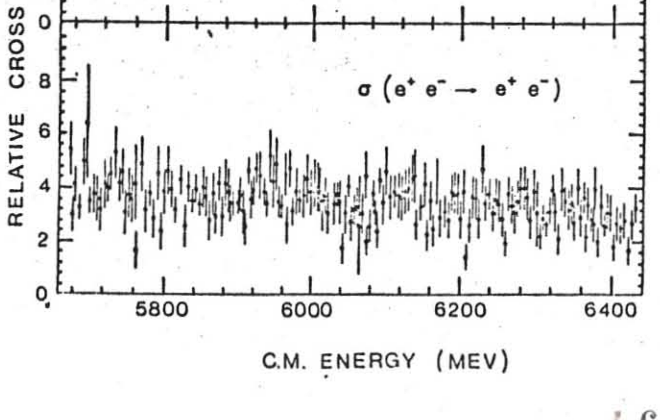


Fig. 2 - The total hadronic cross section normalized to small e^+e^- pairs and the Bhabha cross section measured for large angle e^+e^- pairs.

show no significant peaks. The sensitivity of the scan depends on the width of the resonance and on its mass ; if ΔW is the c.m. energy resolution :

$$\int \sigma_h(W)\, dW = \frac{2\pi^2}{m^2}(2J+1)\frac{\Gamma_e \Gamma_f}{\Gamma} \quad \text{for} \quad \Gamma \ll \Delta W \, , \tag{2}$$

$$\sigma_{peak} = \frac{12\pi}{m^2} B_e \quad \text{for} \quad \Gamma \gg \Delta W \, . \tag{3}$$

Fig. 3 shows the fitted values of $\int \sigma_h dW$ from the data of Fig. 2 as a function of the mass and for different assumption on Γ. Numerical results are shown in Table I.

TABLE I

m(GeV)	$\int\sigma$(W)dW (nb · MeV)		
	$\Gamma \sim 0$	Γ = 10 MeV	Γ = 50 MeV
5.7 - 5.19	96	110	161
5.9 - 6.1	66	101	222
6.1 - 6.4	85	108	151

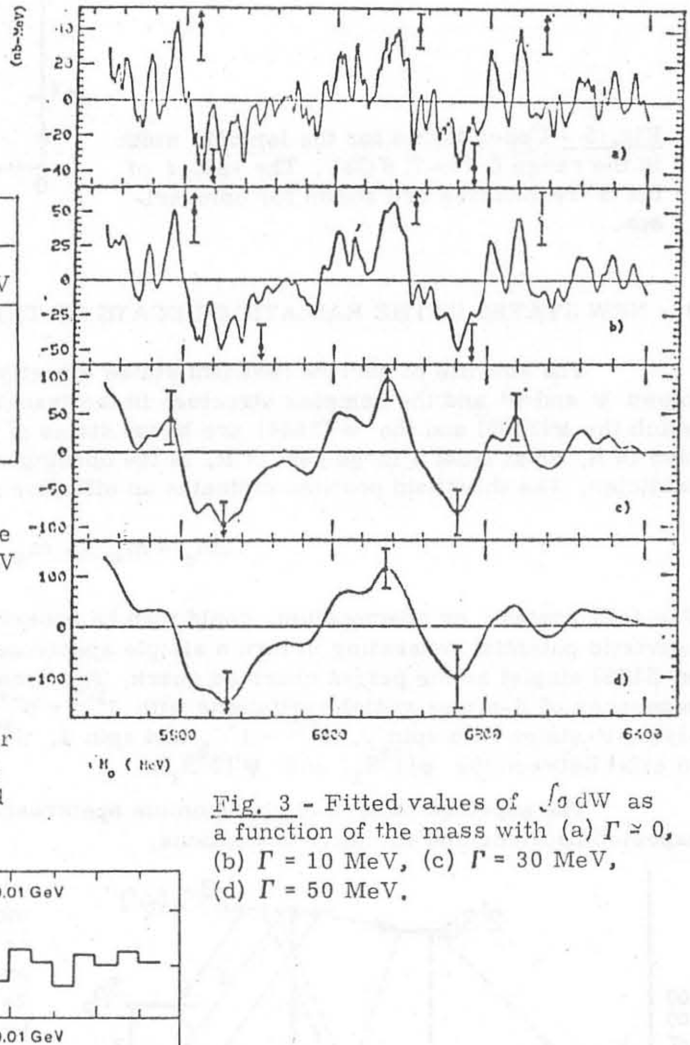


Fig. 3 - Fitted values of $\int \sigma\, dW$ as a function of the mass with (a) $\Gamma \simeq 0$, (b) Γ = 10 MeV, (c) Γ = 30 MeV, (d) Γ = 50 MeV.

Quantitatively these measurements can be translated to a leptonic width $\Gamma_e \lesssim 150$ eV for a narrow state ($\Gamma \simeq 0$, 95% c.l.) or to a leptonic branching ratio $B_e \lesssim 6 \times 10^{-6}$ for a resonance wide enough to be resolved (Γ = 70 MeV, 95% c.l.). Similar results[5] from the SLAC-LBL collaboration are shown in Fig. 4, where the upper limits for different widths are given as a function of the mass. The limits reported are rather stringent for vector mesons,

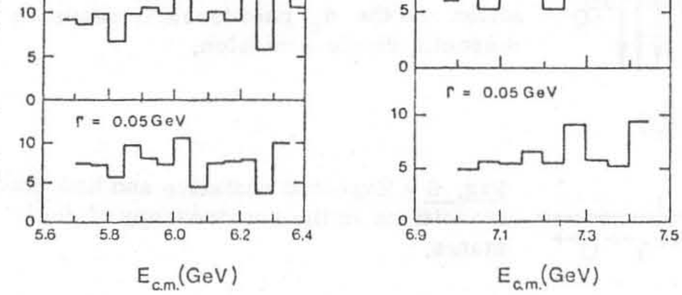


Fig. 4 - Upper limits for leptonic widths and branching ratios under different assumption for Γ as function of mass.

which have typical leptonic widths of several keV.

The present situation concerning the limits on narrow states in the energy range up to 7.6 GeV is depicted in Fig. 5, with contributions from Novosibirsk and Frascati. It is clear that to a limit between one and two orders of magnitude below the ψ leptonic width no narrow resonances are observed.

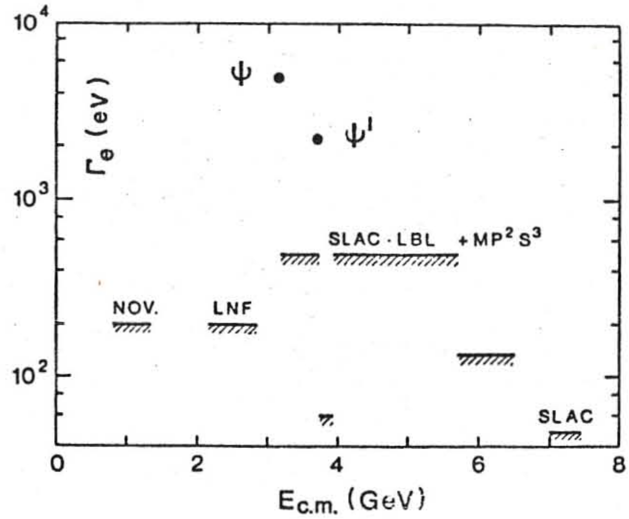


Fig. 5 - Upper limits for the leptonic width in the range 0.78 - 7.6 GeV. The values of the ψ resonances are shown for comparison.

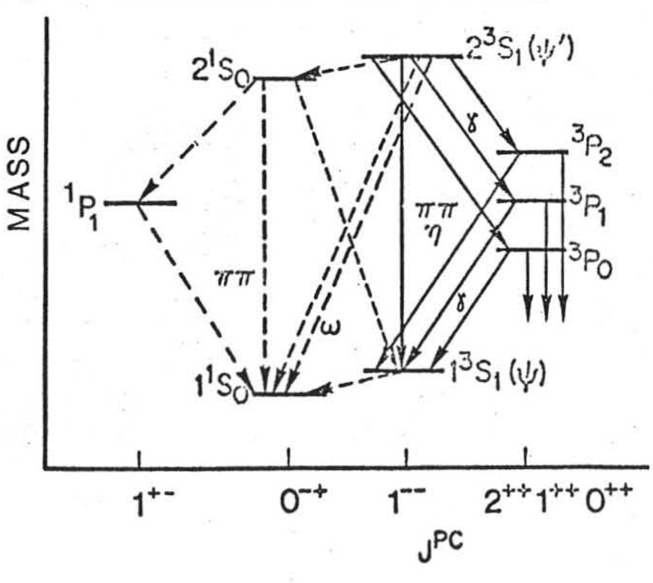
3. - NEW STATES IN THE RADIATIVE DECAYS OF THE ψ-PARTICLES. -

The absence of narrow resonant states directly coupled to the photon other than the known ψ and ψ' and the complex structure in the transition region fit nicely into the picture in which the $\psi(3095)$ and the $\psi'(3684)$ are bound states of a pair of new heavy quarks $(c\bar{c})$ and the rise in R, or at least a large part of it, is the opening of the threshold for production of charmed particles. The threshold position indicates an effective mass m_c = 1.6 - 2 GeV from which

$$2m_c - m_\psi << m_\psi . \qquad (4)$$

The $(c\bar{c})$ system, or charmonium, could than be described, at least to first order, by a non-relativistic potential generating in turn a simple spectroscopic set of discrete states, each of them an SU(3) singlet as the parent charmed quark. The dynamics of $c\bar{c}$ interaction generates two sequences of S-states radial excitations with $J^{PC} = 0^{-+}(\eta_c)$ and $J^{PC} = 1^{--}(\psi)$. A set of low-lying P-states with spin 0, $J^{PC} = 1^{+-}$, and spin 1, $J^{PC} = 0^{++}$, 1^{++} and $2^{++}(\chi)$ are predicted to exist between the $\psi(1^3S_1)$ and $\psi'(2^3S_1)$.

The expected pattern of charmonium spectroscopy is shown in Fig. 6, together with the expected hadronic and radiative transitions.



The singlet P-state $J^{PC} = 1^{+-}$ is almost impossible to detect in ψ' decays, since γ and π transitions are forbidden by C and I-spin conservation respectively and a 2π mode can be severely suppressed either by phase space or by centrifugal barriers. The triplet P-states $J^{++}(\chi)$ can be reached on the other hand via an electric dipole transition and the η_c pseudoscalar sequence by magnetic dipole-emission.

Fig. 6 - Expected radiative and hadronic transitions in the spectroscopy of $(c\bar{c})$ states.

It is now clear that a systematic study of the radiative decays of the vector (ψ) particles can yield information

a) on the nature and the decay modes of the new particles ;
b) on the existence of new C-even states not accessible in the one-photon channel ;
c) on masses, quantum numbers and transition strengths between the principal sequences.

All this information, together with data on the hadronic decays of states in all three sequences, can represent the experimental constraint on the possible charmonium models and therefore the most direct way of determining through the simple ($c\bar{c}$) system the dynamics of quark-quark interaction.

3. 1. - Inclusive photon spectra.

One clear prediction of the charm model is that, besides the main vector sequence, new states, either pseudoscalar or P-wave states, should exist and could be reached by radiative transitions from the ψ'. These states could decay into the ψ (whenever kinematically possible) again by electromagnetic transition, or directly into ordinary hadrons.

Experimentally at least three states, all with C = +1, have been found in decays via one photon emission from the $\psi'(3684)$ and the $\psi(3095)$.

The energy spectrum of photons measured[6] by the MP^2S^3 collaboration is shown in Figures 7 and 8 for ψ and ψ' decays respectively. The shape of the spectra plotted on a logarithmic energy scale (due to the almost constant fractional resolution of the NaI counters used in this experiment) is largely dominated by production and subsequent decays of neutral pions, as shown

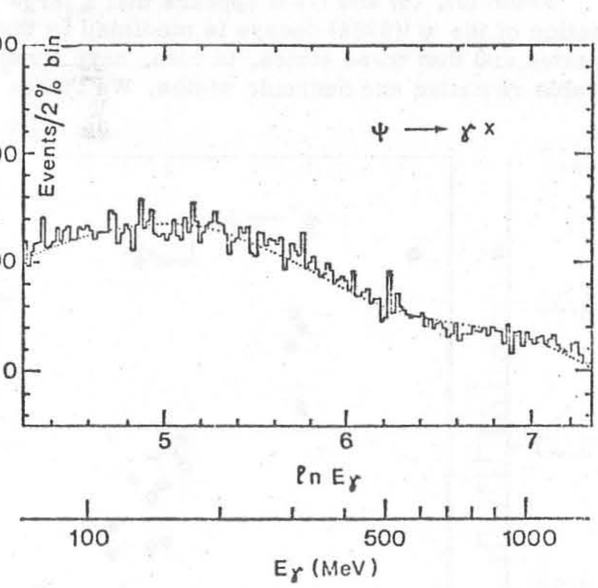


Fig. 7 - The inclusive γ ray distribution at the $\psi(3095)$ mass in ln E_γ for 27020 events.

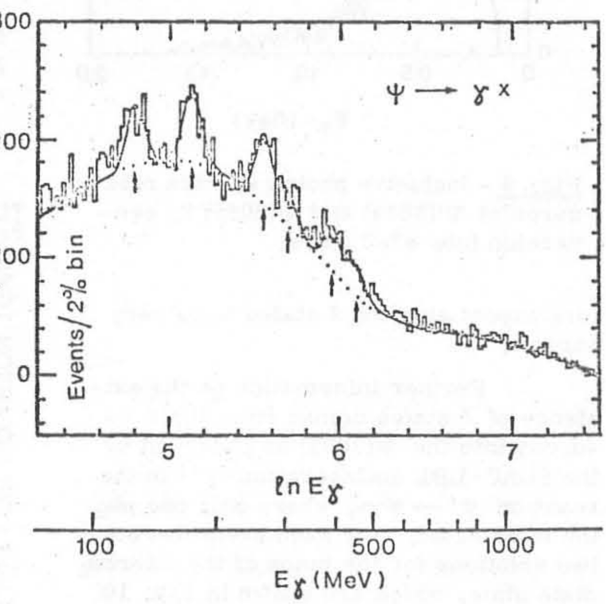


Fig. 8 - The inclusive γ ray distribution at the $\psi'(3684)$ mass in ln E_γ for 37171 events. A fit to the observed structures is also shown.

by the dotted lines. The data, consisting of events with one or more γ rays accompanied by at least two charged particles, show no statistically significant structure in the $\psi(3095)$ spectrum. At the $\psi'(3684)$ mass, on the other hand, three major peaks at energies of 121, 169 and 260 MeV appear with widths consistent with the resolution, together with smaller bumps at 304, 390 and 448 MeV.

The first three peaks can be attributed to the decay $\psi'(3684) \to \gamma\chi$ with $M_\chi = 3561$, 3511 and 3414 MeV ; the higher energy structures are compatible with the subsequent decays $\chi \to \gamma\psi(3095)$.

Preliminary values of the branching ratios are $(6 \pm 2)\%$, $(8 \pm 2)\%$ and $(7 \pm 2)\%$ for the primary transitions and of the order of 40 to 60% for the secondary transitions. This implies, for the $\psi'(3684)$ decays, that

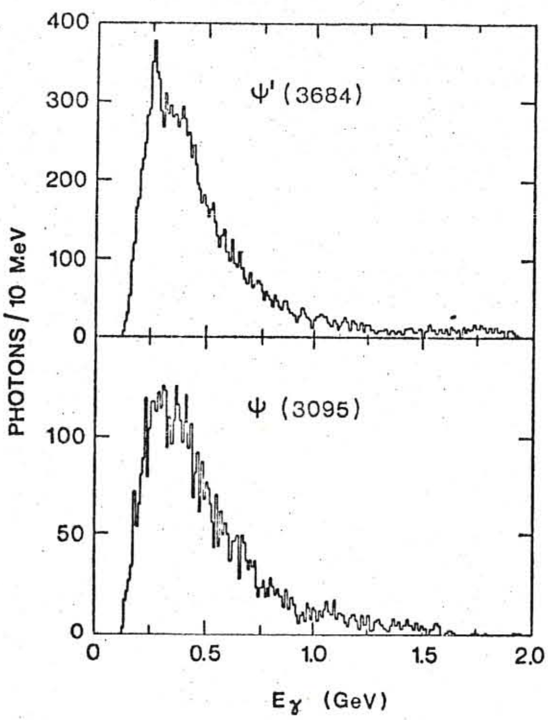


Fig. 9 - Inclusive photon spectra measured at $\psi'(3684)$ and $\psi(3095)$ by conversion into e^+e^- pairs.

$$\sum_{\chi} \frac{\Gamma(\psi' \to \gamma\chi)}{\Gamma(\psi' \to \text{all})} \simeq (21 \pm 3)\% \tag{5}$$

$$\sum_{\chi} \frac{\Gamma(\psi' \to \gamma\chi)}{\Gamma(\psi' \to \text{all})} \frac{\Gamma(\chi \to \gamma\psi)}{\Gamma(\chi \to \text{all})} \simeq (11 \pm 3)\% \tag{6}$$

and consequently

$$\sum_{\chi} \frac{\Gamma(\psi' \to \gamma\chi)}{\Gamma(\psi' \to \text{all})} \frac{\Gamma(\chi \to \text{hadrons})}{\Gamma(\chi \to \text{all})} \simeq (10 \pm 3)\% \tag{7}$$

The radiative branching ratio to the $\chi(3415)$ is confirmed by an inclusive γ spectrum obtained(7) by the SLAC-LBL collaboration, yielding a value of $(6.5 \pm 2.2)\%$ (for a $1 + \cos^2\theta$ distribution; see next section). The spectrum, shown in Fig. 9, has a 5 σ peak at 261 ± 5 MeV with a width consistent with the resolution, other peaks being probably unresolved.

From (5), (6) and (7) it appears that a large fraction of the $\psi'(3684)$ decays is mediated by the χ states and that these states, in turn, have considerable radiative and hadronic widths. We therefore expect also the χ states to be very narrow.

Further information on the existence of χ states comes from their γ-decay into the $\psi(3095)$ as observed by the SLAC-LBL collaboration(5, 7) in the reaction $\psi' \to \psi\gamma\gamma$, where only one photon is detected. For each event there are two solutions for the mass of the intermediate state, which are shown in Fig. 10. There is clear support for a state at 3.5 GeV, four events cluster at 3.55 GeV and another four at 3.45 GeV. One event at 3.46 GeV is also reported by the DASP collaboration at DORIS(8). We have therefore suggestions for a fourth C = + state around 3.45 GeV, which at present is not clearly observed as a radiative decay product of the $\psi'(3684)$.

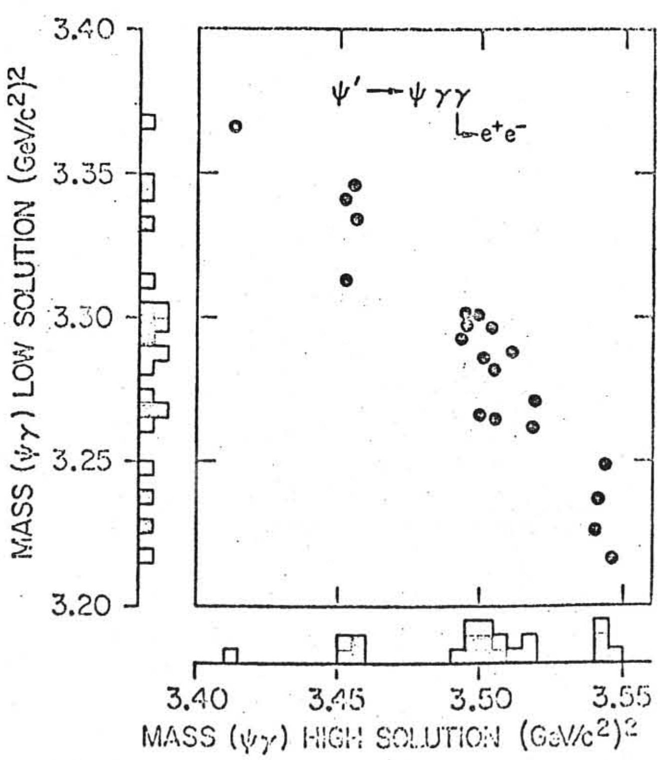


Fig. 10 - Scatter plot of the two solutions for the mass of intermediate states in decays $\psi' \to \psi\gamma\gamma$.

As partial conclusions, limited to the electromagnetic transitions of the ψ particles to new states, there is evidence for three major transitions of the $\psi'(3684)$ with comparable branching ratios and consituting a significant part of the ψ' decay rate and the subsequent decays $\chi \to \gamma\psi$ have also been observed. The relative size of the six branching ratios, which are simultaneously measured(6), rule out any possible ambiguity in the mass assignements of these states. There is some evidence for a fourth C-even state decaying into $\psi\gamma$, which may correspond(9) to the first radial recurrence of the pseudoscalar η_c. The η'_c is in fact expected to lie in the same range of mass of the three established χ states.

3.2. - Hadronic decays of the χ states.

The data sample for this study consists of 2-, 4- and 6-prong events with zero total charge and one missing photon at the energy of the $\psi'(3684)$. The invariant mass spectra of all hadrons in the final state for events fitted to the reactions :

$$\psi'(3684) \to \gamma\chi \quad \begin{cases} \to 2\pi^+ 2\pi^- \\ \to 3\pi^+ 3\pi^- \\ \to \pi^+\pi^- K^+K^- \\ \to \pi^+\pi^- \text{ or } K^+K^- \end{cases} \qquad (8)$$

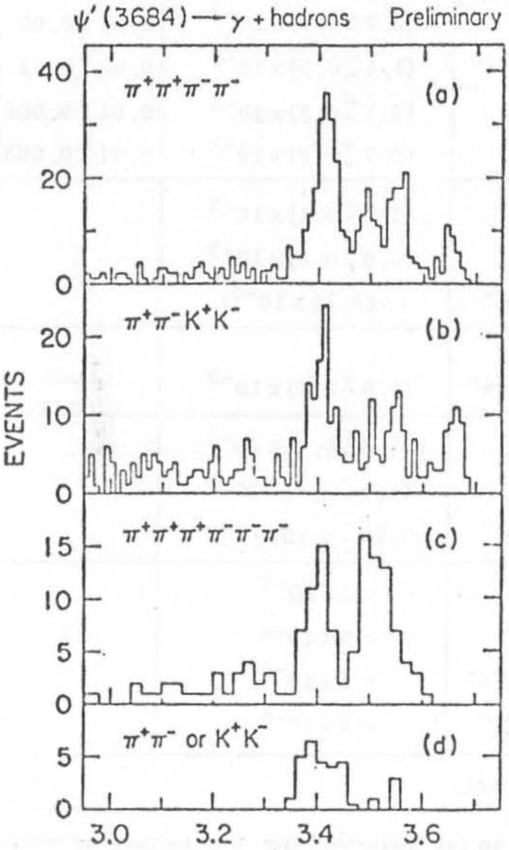


Fig. 11 - Invariant mass spectra for events from the reaction $\psi' \to \gamma +$ + hadrons for various hadronic final states.

are shown in Fig. 11. Neglecting events with masses above 3.6 GeV, which are compatible with second-order electromagnetic decays of the ψ', three clearly separated peaks appear at masses of 3415, 3500 and 3550 MeV (Fig. 11a). The observed widths are similar and consistent with the experimental resolution. The resolution is worsened when final states of increasing complexity (e.g. $2\pi 2K$, 6π) are selected. There is no evidence in the data for a hadronic decay mode of a state at 3450 MeV that seems to be only detected in the $\psi' \to \psi\gamma\gamma$ reaction.

The two-prong events, in spite of the low statistics, show a signal at 3415 MeV and a considerably weaker evidence for the 3550 MeV state.

The hadronic decays of C-even states give therefore independent support to the results on the radiative transitions between ψ and ψ' discussed above. In addition the decay of a C = + object into two pseudoscalars is particularly interesting, since only states with both even spin and parity can decay to this mode(10). If then both $\pi^+\pi^-$ and K^+K^- are present, as indicated for the 3.41(7), then I = 0(10), which supports the assignement of the $\chi(3.41)$ to $I^G = 0^+$, $J^{PC} = (\text{even})^{++}$. This rules out a pseudoscalar and is what expected for a L = 1, 0^{++} or $2^{++}(c\bar{c})$ state. Additional information on the spin of the χ states is given by the angular distribution of the photon in reaction (8), relative to the incident beam direction.

The data relative to the three χ states are presented in Fig. 12. The distribution for $\chi(3.41)$, with a value of a compatible with 1, suggests a J = 0 assignement. The DESY-Heidelberg group at DORIS has demonstrated that the $\chi(3.50)$ has nonzero spin(11).

A summary of the known hadronic decay modes of the χ states is given in Table II.

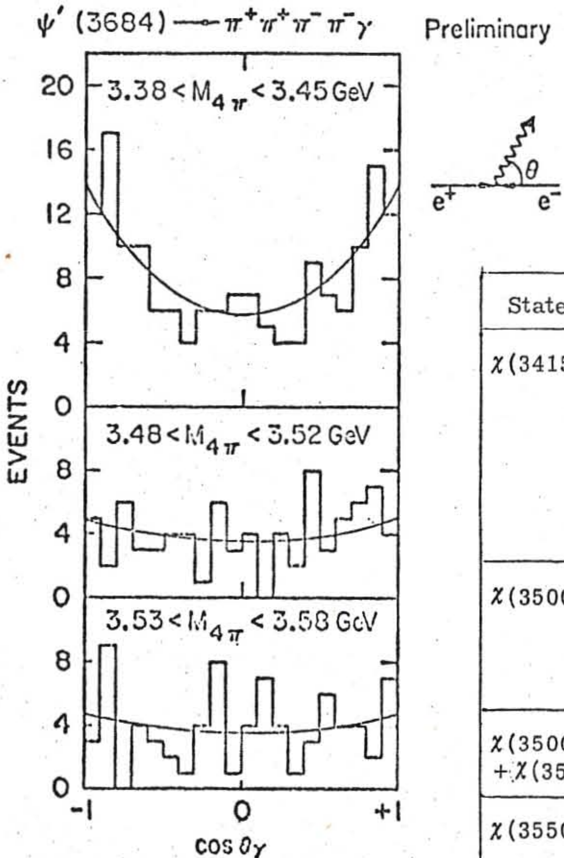


Fig. 12 - Distributions in cos θ for three different intervals of the 4π invariant mass. $1+a\cos^2\theta$ fits are shown with $a=1.4\pm0.4$, $a=0.25\pm0.5$, and $a=0.2\pm0.4$ in the low, intermediate and high mass region respectively.

TABLE II

State	Decay mode f	$BR(\psi' \to \chi\gamma) \times BR(\chi \to f)$	$BR(\chi \to f)$
$\chi(3415)$	$\pi^+\pi^-\pi^+\pi^-$	$(3.2\pm0.6)\times10^{-3}$	0.05 ± 0.02
	$\pi^+\pi^-K^+K^-$	$(2.7\pm0.7)\times10^{-3}$	0.04 ± 0.02
	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$(1.4\pm0.5)\times10^{-3}$	0.02 ± 0.01
	$\pi^+\pi^-$	$(0.7\pm0.2)\times10^{-3}$	0.01 ± 0.005
	K^+K^-	$(0.7\pm0.2)\times10^{-3}$	0.01 ± 0.005
$\chi(3500)$	$\pi^+\pi^-\pi^+\pi^-$	$(1.1\pm0.4)\times10^{-3}$	
	$\pi^+\pi^-K^+K^-$	$(0.6\pm0.3)\times10^{-3}$	
	$\pi^+\pi^- + K^+K^-$	$<(0.15\times10^{-3})$	
$\chi(3500)+$ $+\chi(3550)$	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$(2.5\pm0.8)\times10^{-3}$	
$\chi(3550)$	$\pi^+\pi^-\pi^+\pi^-$	$(1.6\pm0.4)\times10^{-3}$	
	$\pi^+\pi^-K^+K^-$	$(1.4\pm0.4)\times10^{-3}$	
	$\pi^+\pi^- + K^+K^-$	$(0.23\pm0.12)\times10^{-3}$	
$\chi(3450)^*$	$\pi^+\pi^-\pi^+\pi^-$	$<4\times10^{-4}$	
	$\pi^+\pi^-K^+K^-$	$<5\times10^{-4}$	
	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$<7\times10^{-4}$	
	$\pi^+\pi^- + K^+K^-$	$<3\times10^{-4}$	

* - 90% confidence level.

In their hadronic and electromagnetic decays so far observed the χ's behave as would be expected for C = G = + states : reached by emission of one photon from the $\psi'(3684)$, decay channels through γ transitions as well as with even numbers of pions are observed. Three states are observed in their production and in both decay modes ; we identify the 0^{++} level with the lightest and tentatively 1^{++} and 2^{++} levels with the intermediate and with the heaviest respectively, as suggested by a simple spin-orbit splitting arising from the short-distance coulomb component of the potential. A fourth state is probably present as a candidate for the recurrence of the pseudoscalar paracharmonium. The existence of the η_c, the expected pseudoscalar ground state $J^{PC}=0^{-+}$ in the charmonium spectroscopy, is on the other hand still dubious. Data(12) on a $J\neq1$, C = + state at 2.85 GeV are not supported by the inclusive γ ray spectra both of the MP^2S^3 and of the SLAC-LBL collaborations (see Figs. 7 and 9) to the level of the present statistical accuracy.

4. - THE TRANSITION REGION AND THE ψ SPECTROSCOPY. -

The experimental information on e^+e^- annihilation in the so called transition region shows, as can be seen in Fig. 1, an impressive doubling of the value of R across an energy interval as narrow as 0.5 GeV. Structures sit on top of this already startling phenomenon, thus adding to the complexity of any answer to the immediate question on how does hadron production at the 4.1 GeV enhancement differ from hadron production nearby the enhancement. A close investigation of the properties of hadron and lepton production in this energy region could provide information on:

a) the existence of new vector states, possible heavy partners of the narrow ψ states in the charmonium picture ;
b) the final states which exhibit the explicit dynamics responsible for such a concentration of phenomena on a small energy scale.

4.1. - New vectors and the ψ spectroscopy.

Detailed measurements of R in the 4 GeV region(19) are shown in Fig. 13. The main features of the data in this energy region are first a structure at 3.95 GeV, followed by a very sharp rise of R, which grows by 50% in only 20 MeV. Around 4.1 GeV a broad peak with evidence for substructure can be observed, followed by a clear resonant behaviour at 4.4 GeV. For a number of reasons it is difficult to specify the exact number of states and obtain the corresponding widths and integrated cross sections.

First, the shape of the background in the transition region is not known. Secondly, all of this rapid cross section variation is taking place in a single angular momentum channel, and the resonances may strongly interfere with each other. Thirdly, threshold production of new particles, as suggested by the behaviour of the transition region, may badly distort the shape of a Breit-Wigner line. A state $\psi(4414)$ is on the other hand well separated and the BW fit is shown in Fig. 14.

Table III lists the main resonance parameters compared to those of the $\psi(3095)$ and $\psi'(3684)$.

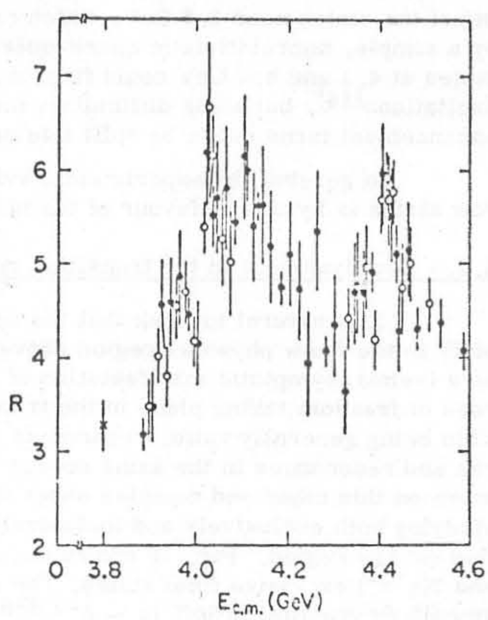


Fig. 13 - R versus c.m. energy in the 4 GeV region. Open and full points correspond to two different sets of data.

TABLE III

State	Mass (MeV)	Γ (MeV)	Γ_e (keV)
$\psi(3095)$	3096 $\pm$ 4	0.069 $\pm$ 0.015	4.8 $\pm$ 0.6
$\psi'(3684)$	3684 $\pm$ 5	0.228 $\pm$ 0.056	2.1 $\pm$ 0.3
$\psi(4414)$	4414 $\pm$ 7	33 $\pm$ 10	0.44 $\pm$ 0.14

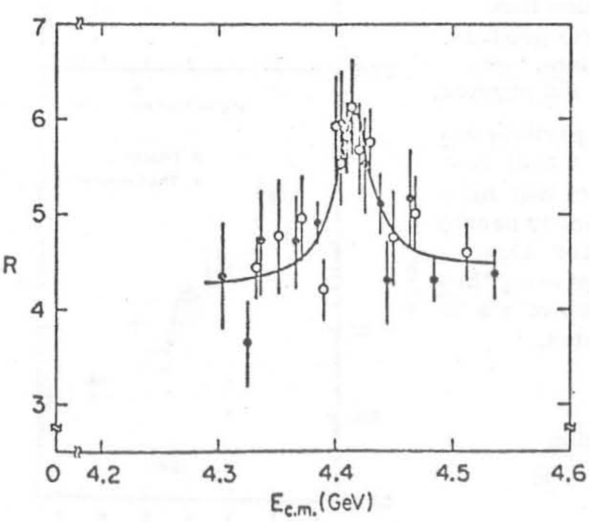


Fig. 14 - R versus c.m. energy near 4.4 GeV. The solid curve is a Breit-Wigner fit to the data.

Considering this structure as a vector particle related to the narrow resonances, its much greater width may indicate that the selection rules responsible for the narrowness of the ψ and ψ' may no longer be operative at 4 GeV.

A summary of all new states and their decay modes is presented schematically in Fig. 15. It resembles closely the picture of the charmonium levels (Fig. 6). Three C-even states $\chi(3.41)$, $\chi(3.50)$ and $\chi(3.55)$ can be assigned to the 0^{++}, 1^{++}, 2^{++} sequence of P-states on the basis of the angular distributions, of the strong $\pi^+\pi^-$ and K^+K^- decays of the $\chi(3.41)$ and of the weaker two-body decays of the $\chi(3.55)$.

A possible fourth state $\chi(3.45)$ is seen to decay to $\psi(3095)\gamma$, but no hadronic modes have been observed. Similarly there is no evidence for hadronic decays of the $\eta_c(2850)$. The problem of the two pseudoscalar states is still open, as well as the exact values of the mass splitting of the states near 3.5 GeV, which cannot be explained by a simple, nonrelativistic quark-quark potential(9). The states at 4.1 and 4.4 GeV could fit into a picture of radial excitations(14), but some difficulties may arise if the 4.1 enhancement turns out to be split into several substates.

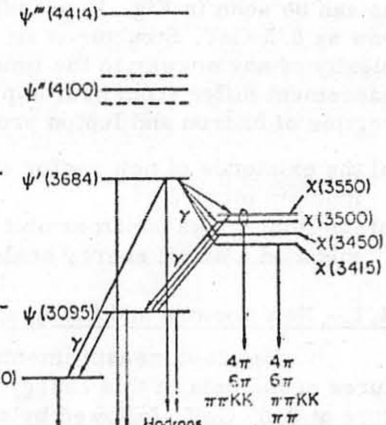


Fig. 15 - Energy level diagram and decay modes of the new states.

In general the experimental evidence on the narrow states is by now in favour of the idea of a new and only one quark in this energy region.

4.2. - New dynamics in the transition region.

It is natural to think that the apparent scaling behaviour of R in the "new physics" region above 5 GeV can be considered as a (semi) asymptotic manifestation of the aperture of new degrees of freedom taking place in the transition region around 4 GeV. This being generally valid, regardless of the presence of structures and resonances in the same energy region, one is led to learn more on this rapid and complex onset of the "new physics" by studying both exclusively and inclusively produced final states in this energy region. Fig. 16 shows the cross sections for $2(\pi^+\pi^-)$ and $3(\pi^+\pi^-)$ exclusive final states. The data are consistent with a smooth exponential falloff ($\sigma \sim s^{-2.8\pm0.5}$ and $\sigma \sim s^{-2.3\pm0.8}$ respectively) with no sign of discontinuity when crossing the 4 GeV region. If on one hand it could be expected that multipion final states be unsensitive of new mechanisms such as charm production, this is not the case for various moments of the data, one obvious place to look for differences between new and old physics.

The mean charged multiplicity and the mean particle momentum are shown in Fig. 17 as they vary across the 4 GeV region. The excellent statistical quality of the data shows that neither structures nor absolute normalization with respect to nearby regions seem to feel the complex R behaviour. Another aspect of the data that fails to show any dramatic change on passing through the region where R varies by a factor 2 is the ratio of π's to K's to p's, or the particle composition of the final states.

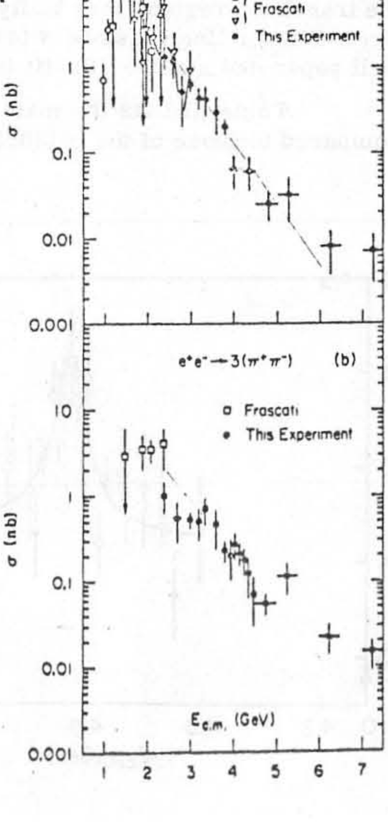
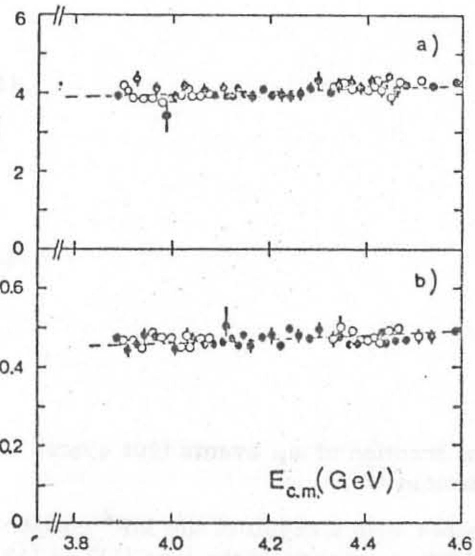


Fig. 16 - a) Total cross section for $2(\pi^+\pi^-)$ production vs c.m. energy. b) Total cross section for $3(\pi^+\pi^-)$ productions vs c.m. energy.



The necessary conclusion is that the dramatic effect observed in R, which we identify as a threshold to a new dynamic regime, produces but subtle changes on the quantities that were expected to bear some signature of the new processes. From this it becomes imperative that further, more refined investigations of final states be performed, in order to detect directly the products of the new states being produced. The results of these investigations are the argument of the following sections.

Fig. 17 - a) Mean charged multiplicity vs c.m. energy in the 4 GeV region. The line is a fit to the same quantity between 2.4 and 7.0 GeV. b) Same as in a) for the mean momentum per track (π mass is assumed).

5. - ANOMALOUS LEPTON PRODUCTION. -

An anomalous component in lepton production has been detected at SPEAR first by the SLAC-LBL collaboration in the $e\mu$ channel(15) and then by the Maryland-Pavia-Princeton collaboration in inclusive muon production(16).

The detection of a clear signal in this anomalous component is one of the strogest indications that pairs of new particles are produced in e^+e^- collisions above 4 GeV. Several new processes could account for these events; the following discussion, although referring specifically to the production of $e\mu$ final states, can be applicable as well to both classes of anomalous lepton production.

A first possibility to explain the production mechanism is given by the two-body decay of a charged vector meson:

$$e^+e^- \rightarrow U^+U^- \quad \begin{cases} \rightarrow e^- \bar{\nu}_e \\ \rightarrow \mu^+ \nu_\mu \end{cases} \tag{9}$$

or two heavy sequential leptons could be produced decaying into three bodies

$$e^+e^- \rightarrow U^+U^- \quad \begin{cases} \rightarrow e^- \bar{\nu}_e \nu_U \\ \rightarrow \mu^+ \nu_\mu \bar{\nu}_U \end{cases} \tag{10}$$

A third possibility is that these events arise from semileptonic decays of charmed (pseudoscalar or vector) mesons(17):

$$e^+e^- \rightarrow D^+D^- \quad \begin{cases} \rightarrow e^- \bar{\nu}_e(\pi^o, K^o) \\ \rightarrow \mu^+ \nu_\mu(\pi^o, K^o) \end{cases} \tag{11}$$

$$\begin{array}{l} e^+e^- \rightarrow D^o\bar{D}^o \\ \quad \lfloor \rightarrow e^-\bar{\nu}_e K^+ \\ \lfloor\!\!\longrightarrow \mu^+\nu_\mu K^- \end{array} \qquad (12)$$

$$\begin{array}{l} e^+e^- \rightarrow D^{*+}\bar{D}^{*-} \\ \quad \lfloor \rightarrow e^-\bar{\nu}_e \\ \lfloor\!\!\longrightarrow \mu^+\nu_\mu \end{array} \qquad (13)$$

5.1. - eμ events.

Table IV shows the upper limits (90% c.l.) on the fraction of eμ events (105 events after background subtraction) accompanied by an undetected particle[15].

TABLE IV

Undetected particle (s)	Upper limit (90% c.l.)
K^o	9%
π^o or γ	18%
charged part.	9%
charged + π^o + γ	11%
	total 39%

These values, together with a result of the MP^2 collaboration[16], show that semileptonic decays of the type (11) or (12) cannot explain the bulk of the effect since most of the eμ events seem to contain only neutrinos.

Evidence that the origin of these events is the decay of a pair of new particles is obtained from the distribution of the collinearity angle between the two prongs (Fig. 18). As characteristic of the decay of a pair of fixed mass particles, the decay products appear to be increasingly collimated back to back as the energy increases.

The momentum spectrum of the detected leptons allows to separate the hypothesis of a two-body decay (9), (13) from a three-body decay (10). In an appropriate variable ρ[18], proportional to the momentum, the distribution of all events is shown in Fig. 19.

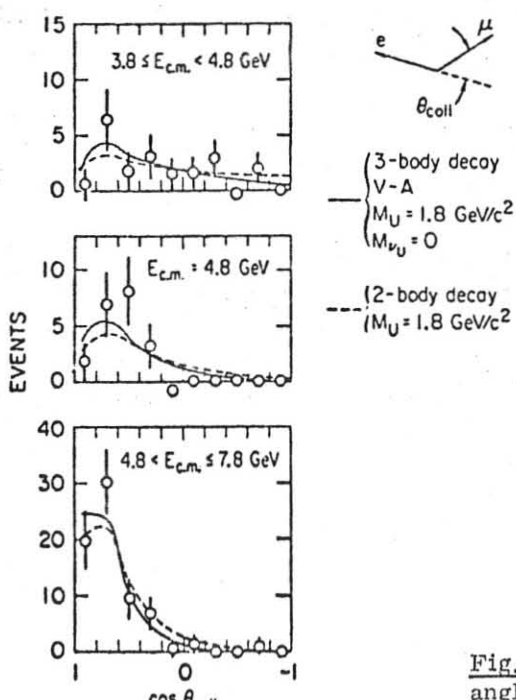


Fig. 18 - Distributions in the cosine of the collinearity angle at different energies.

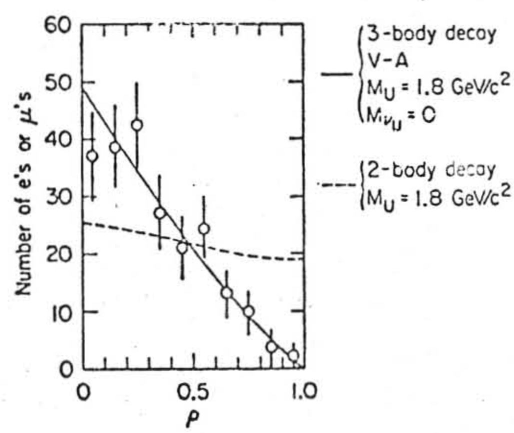


Fig. 19 - Distribution in ρ[18] for events collected between 3.8 and 7.8 GeV.

If a heavy lepton is the source of the eμ events, using eμ universality we expect in general anomalous lepton pairs with cross sections :

$$\frac{1}{2}\,\sigma_{e\mu} = \sigma_{ee} = \sigma_{\mu\mu} . \tag{14}$$

This has been observed and the results are shown in Fig. 20 as a function of c.m. energy. The experimental average values yield :

$$\frac{\sigma_{e^+e^-}}{\sigma_{e\mu}} = 0.39 \pm 0.21 , \qquad \frac{\sigma_{\mu^+\mu^-}}{\sigma_{e\mu}} = 0.66 \pm 0.16 , \tag{15}$$

in good agreement with (14).

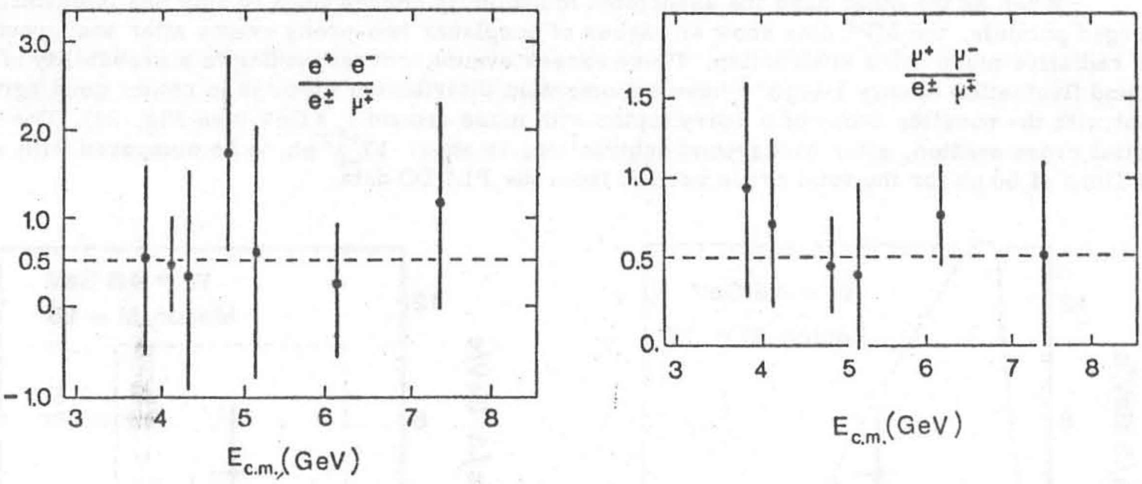


Fig. 20 - Ratio of anomalous e^+e^- and $\mu^+\mu^-$ cross sections to the eμ cross section versus c.m. energy.

The observed (unnormalized) cross section for the eμ events is shown in Fig. 21 at various c.m. energies. A mass m_U = 1.8 GeV and a V-A three body decay are again favoured by the data.

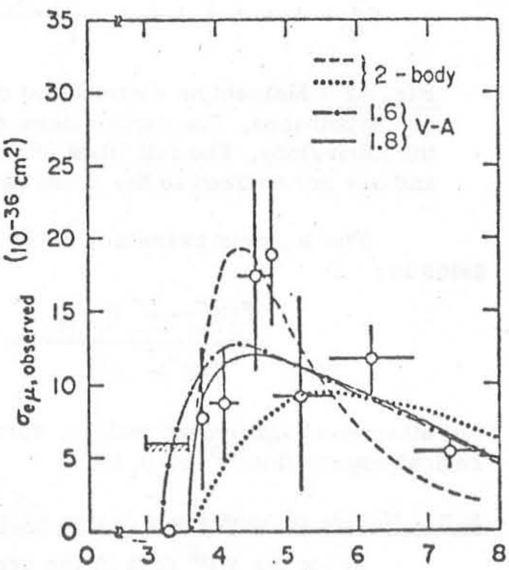


Fig. 21 - Observed eμ production cross section vs. $E_{c.m.}$. Curves labelled V-A refer to a heavy lepton, M_U = 1.6 or 1.8 GeV, M = 0. Dotted and dashed curves refer to a heavy boson with constant and s^{-1} form factors respectively.

5. 2. - Inclusive muon production.

Single inclusively produced muons having momenta above 1 GeV/c have been detected by the Maryland-Pavia-Princeton (MP^2) and by the PLUTO collaboration. When the charged multiplicity associated to the detected muon is $\gtrsim 2$ we have :

$$(MP^2)^{(16)} \quad \left.\frac{d\sigma}{d\Omega}\right|_{90^0} (\mu + \gtrsim 2) < 7.5 \text{ pb/sr} \qquad \text{at } 4.8 \text{ GeV}$$

$$(PLUTO)^{(19)} \quad \sigma(\mu + \gtrsim 2) < 70 \text{ pb} \qquad \text{at } 4\text{-}4.5 \text{ GeV} . \qquad (16)$$

These values put severe limits on semileptonic decays of charmed mesons such as (11) or (12) in this energy region.

When on the other hand the associated multiplicity corresponds to only one (unidentified) charged particle, the MP^2 data show an excess of acoplanar two-prong events after background and radiative muon pairs subtraction. These excess events, corresponding to a probability of background fluctuation of only 1.4×10^{-2}, have a momentum distribution which is in rather good agreement with the possible decay of a heavy lepton with mass around 1.8 GeV (see Fig. 22). The differential cross section, after background subtraction, is about 17^{+12}_{-9} pb, to be compared with an upper limit of 80 pb for the total cross section from the PLUTO data.

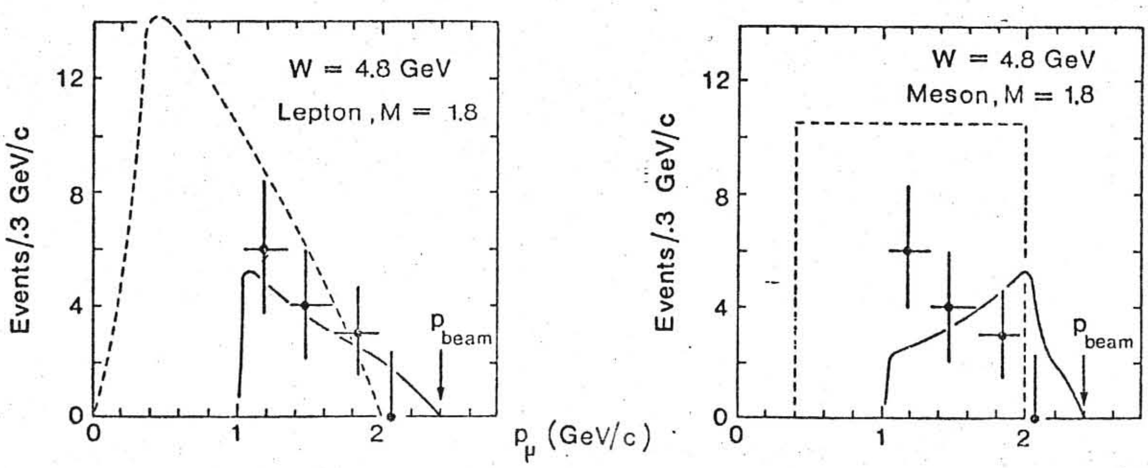


Fig. 22 - Momentum distribution of anomalous muons compared with heavy lepton and meson hypotheses. The dashed lines show the unnormalized decay momentum distributions in the laboratory. The full lines show the effect of QED background and apparatus acceptance and are normalized to the event sample.

The leptonic branching ratio for the decay of the hypothetical heavy lepton that one obtains is :

$$\frac{\Gamma(U^- \to e^- \bar{\nu}_e \nu_U)}{\Gamma(U^- \to \text{all})} = \frac{\Gamma(U^- \to \mu^- \bar{\nu}_\mu \nu_U)}{\Gamma(U^- \to \text{all})} = 0.15^{+0.10}_{-0.08} \qquad (17)$$

in rather good agreement with the corresponding value from $e\mu$ events of $0.17^{+0.06}_{-0.03}$ and the theoretical expectation[30] of 0.18.

5. 3. - Nature of anomalous lepton events.

From the MP^2 data in the previous section it is possible to independently assess that charm cannot be the only source of the detected anomalous muons[20] ;

$$\frac{\frac{d\sigma}{d\Omega}(\mu + \gtrsim 2)}{\frac{d\sigma}{d\Omega}(\mu + 1)} = \frac{\Gamma(U^{\pm} \to \gtrsim 3 \text{ charg. part.})}{\Gamma(U^{\pm} \to 1 \text{ charg. part.})} \lesssim 0.44 \qquad (18)$$

to be compared with predictions[21] for charmed meson decays :

$$\frac{\Gamma(D^{\pm},\ F^{\pm} \to \gtrsim 3 \text{ ch.})}{\Gamma(D^{\pm},\ F^{\pm} \to 1 \text{ ch.})} \gtrsim 2 \ . \qquad (19)$$

In addition the energy dependence of the $e\mu$ cross section, which is compatible with s^{-1} but hardly consistent with higher powers of $1/s$ (see Fig. 21), contradicts any charm hypothesis. The probability of pair production of charmed particles should in fact decrease with rather high powers of $1/s$ due to the form factors involved.

We can therefore reach the following conclusions :

- anomalous lepton production exists with a threshold around 4 GeV;
- the events are consistent with the hypothesis of pair production of new particles undergoing a subsequent 3-body decay;
- for the $e\mu$ events the neutral component of the final state is essentially dominated by neutrinos ;
- the events cannot be explained by the decay of only charmed particles ;
- the kinematics of the decay, the production rates and the leptonic branching fractions are consistent with the hypothesis of a heavy lepton with mass $m \simeq 1.8$ GeV being produced.

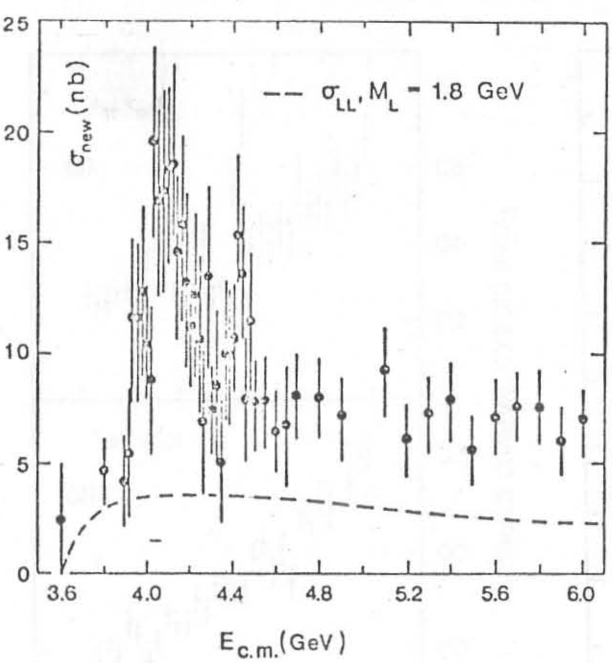


Fig. 23 shows the cross section for "new physics", namely

$$\sigma_{new} = \sigma_h - 2.5\,\sigma_{\mu\mu} \qquad (20)$$

which corresponds to the excess of R above the value of 2.5 in the first scaling region (see Fig. 1). The contribution from a heavy lepton is certainly not negligible, but largely insufficient to explain the values of the cross section even in the second scaling plateau. The message that this picture couveys is that, in addition to possible heavy leptons, other degrees of freedom are apparently excited in the transition region, as we expect from the experimental situation on the "hidden charm" spectroscopy discussed in the previous sections.

Fig. 23 - The cross section for the "new physics" as a function of c.m. energy (see text). The dotted line is the contribution from a heavy lepton with mass of 1.8 GeV.

6. - SEARCH FOR CHARMED MESONS. -

If the behaviour of the hadronic cross section in the transition region is somehow related to the threshold for the production of new mesons, the mass of these objects should lie between 1.84 GeV and 1.95 GeV, the lower limit being set by the narrow width of the $\psi'(3684)$ and the upper limit by the rise in R near 3.9 GeV.

New, heavy, narrow mesons decaying into strange states have been found at SPEAR in the invariant mass distributions of two, three and four body systems above the 4 GeV threshold. Electron-hadrons and electron-K^0_S signals have been observed at DORIS by the DASP and PLUTO collaborations in the same energy region. A posssible monochromatic γ ray transition has also been observed by the MP^2S^3 collaboration at SPEAR around 4.2 GeV.

Experimental evidence is building up that decays of charmed objects have been identified and that a new spectroscopy associated with the production of this quantum number is beginning to emerge.

6.1. - New particles at SPEAR.

Narrow peaks near 1.87 GeV have been observed[22] by the SLAC-LBL collaboration in the invariant mass spectra for neutral combinations of the charged particles $K^{\pm}\pi^{\mp}$ and $K^{\pm}\pi^{\mp}\pi^{+}\pi^{-}$ in the c.m. energy range between 3.9 and 4.6 GeV. The observed widths are smaller than the experimental resolution. Both states have a statistical significance in excess of 5 s.d.; data for the $K^{\pm}\pi^{\mp}$ combinations are shown in Fig. 24 at E_{cm} = 4.03 GeV where R displays both a peak value and a sharp discontinuity (see Fig. 13).

The agreement in mass, width and recoil spectrum for the observed peaks strongly suggest they represent different decay modes of the same object with mass of 1.865 ± 0.015 GeV and FWHM less than 40 MeV (90% c.l.). A new, narrow charged state, with the same properties as the neutral one, has also been found[23]. It is 11 ± 11 MeV heavier, with a mass of 1.876 ± 0.015 GeV, and decays into the exotic channel $K^{\mp}\pi^{\pm}\pi^{\pm}$, but not into the normal K^* channel $K^{\pm}\pi^{+}\pi^{-}$ as shown in Fig. 25. No structure is seen in any other combination of three charged particles[24], as well as in doubly charged modes as $K^{\pm}\pi^{\pm}$, $K^{\pm}\pi^{\pm}\pi^{+}\pi^{-}$ or $K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\pm}$.

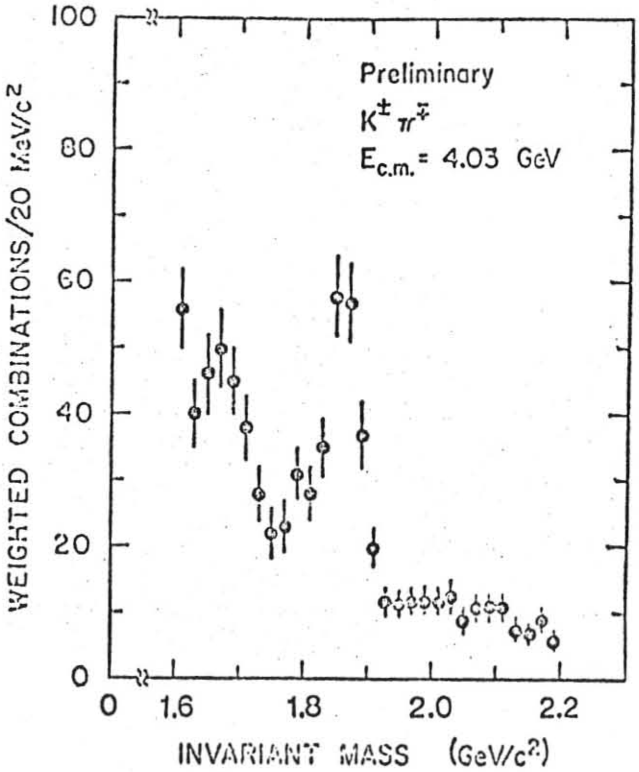


Fig. 24 - Invariant mass distribution of neutral $K\pi$ combinations weighted by $K\pi$ TOF probability at 4.03 GeV c.m. energy.

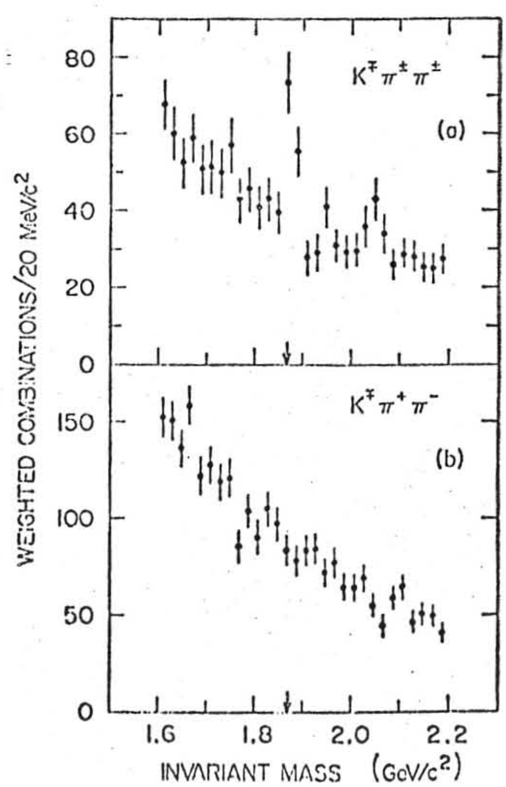


Fig. 25 - Invariant mass spectra for $K\pi\pi$ combinations at 4.03 c.m. energy: (a) $K^{\mp}\pi^{\pm}\pi^{\pm}$; (b) $K^{\mp}\pi^{+}\pi^{-}$.

The observed threshold behaviour, as well as the narrow widths and (for the charged state) the exotic charge-strangeness decay pattern of these states argue against the interpretation of these structures as being a conventional strongly decaying kaon recurrence. Charmed non-strange mesons are expected to exist in a number of spectroscopic states, the lower ones being a pseudoscalar isodoublet D_o-D_+ followed by an "hyperfine" isodoublet partner D_o^*-D_+^*, predicted[25] to be about one pion mass heavier than D_o. The electromagnetic splittings are expected[26] to give

$$D_+^* - D_o^* \simeq D_+ - D_o \simeq 15 \text{ MeV}. \qquad (21)$$

If we identify[23, 27] the observed charged and neutral states with D_+ and D_o, we expect these particles to undergo associated production in (charm-conserving) electromagnetic interaction such as their production by e^+e^- annihilation. The measured spectrum of invariant mass recoiling against the 1865 MeV D_o neutral state, shown in Fig. 26, has no peak at the same mass but actually shows a two-peak structure between 2 and 2.15 GeV.

Similarly the invariant mass spectrum recoiling against the 1876 MeV D_+ charged state, shown in Fig. 27, displays a sharp structure around 2 GeV.

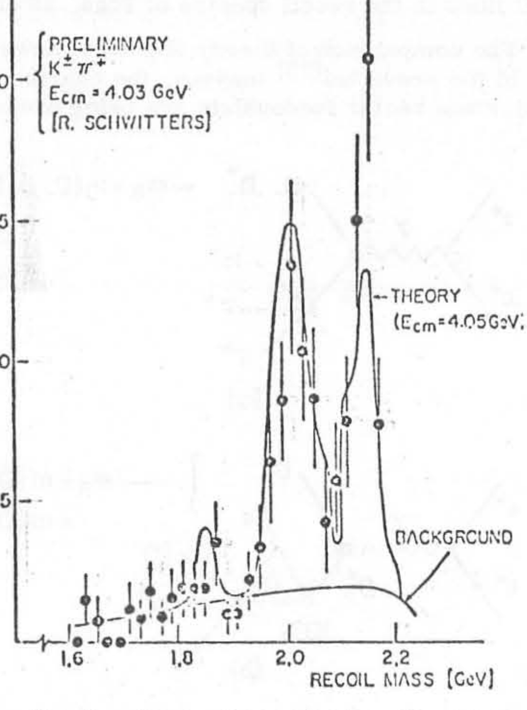


Fig. 26 - Spectrum of invariant masses recoiling against a D_o(1865) and theoretical prediction[27] (see text).

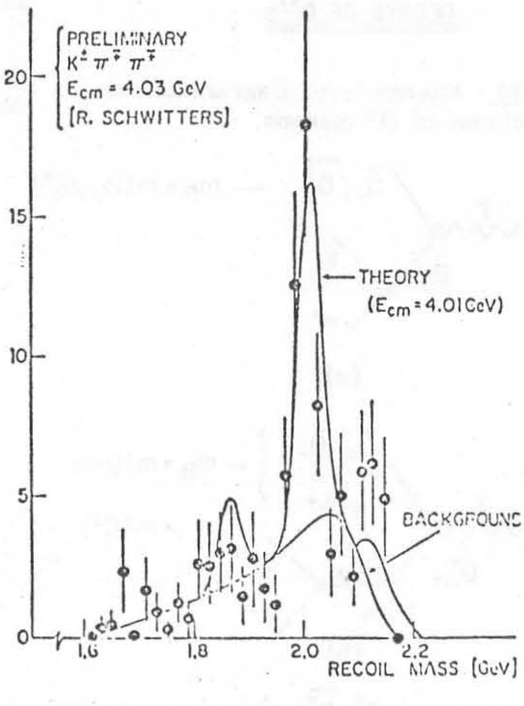


Fig. 27 - Spectrum of invariant masses recoiling against a D_+(1876) and theoretical prediction[27] (see text).

These structures may be associated with the vector isodoublet of D^*'s. The mass difference between the two multiplets is roughly one pion mass. This accident, together with the electromagnetic splittings (21), play a crucial role in determing the $D^* \to D\pi$ branching ratios, with phase space inducing large isospin violation as shown in Fig. 28. In this scheme the masses are assumed to be[27]:

$$m(D_o) = 1.86 \text{ GeV} \qquad m(D_+) = 1.875 \text{ GeV}$$
$$m(D_o^*) = 2.0 \text{ GeV} \qquad m(D_+^*) = 2.015 \text{ GeV}. \qquad (22)$$

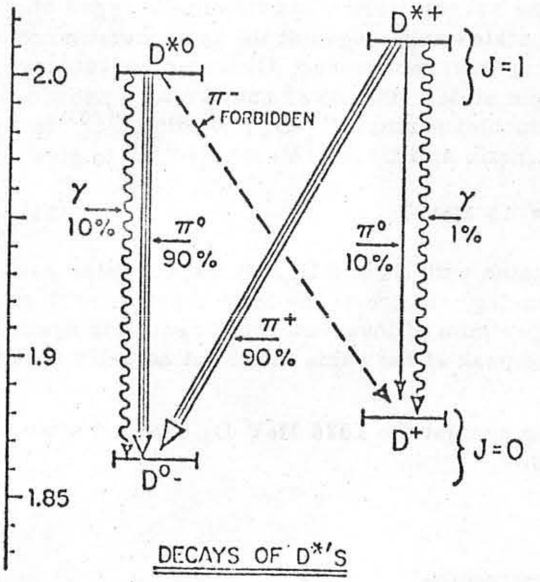


Fig. 28 - Energy level diagram and decay scheme of D^* mesons.

Close to charm threshold the $D\bar{D}$, $D\bar{D}^*$ and $D^*\bar{D}^*$ channels are expected to be dominant, with many body channels like $D^*\bar{D}^*$ + pions taking over as the energy increases. Neglecting mass differences and close to threshold in a quark model the production ratios can be roughly expected to be[27]

$$D\bar{D} : D^*\bar{D} + D\bar{D}^* : D^*\bar{D}^* \simeq 1 : 4 : 7 . \tag{23}$$

This already shows that $D\bar{D}$ production tends to be, as experimentally observed, rather small. In addition, again close to threshold and because of the D^*-D splitting, other narrow structures are produced by kinematical reflections, as shown by the diagrams of Figs. 29 and 30. The branching ratios for the decays of Fig. 28 drive the extent to which a reflection in the D_0 recoil spectrum is much stronger than in the D_+ case. The theoretical predictions are shown as full lines in the recoil spectra of Figs. 26 and 27.

The comparison of theory and data shows that, close to the predicted[25] masses, the charmed pseudoscalar and vector isodoublets are being produced.

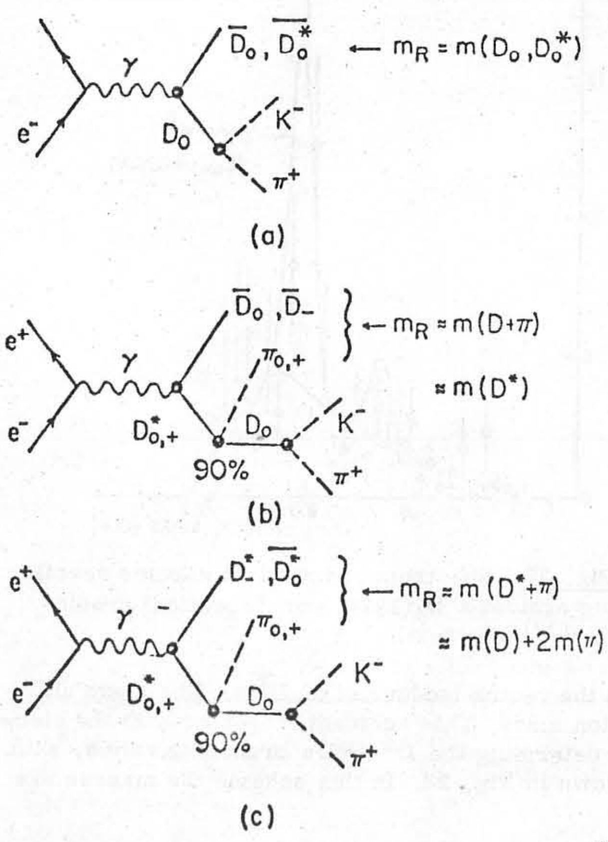


Fig. 29 - Diagrams corresponding to DD, DD^* and D^*D^* production. The mass peaks recoiling against a detected D_0 are real for case (a) and kinematic reflections for (b) and (c). Typical weights are indicated.

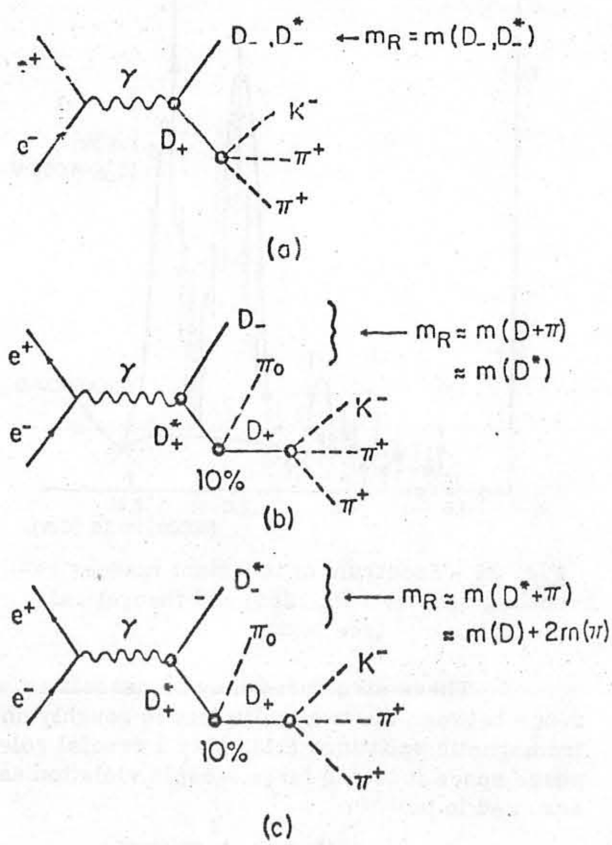
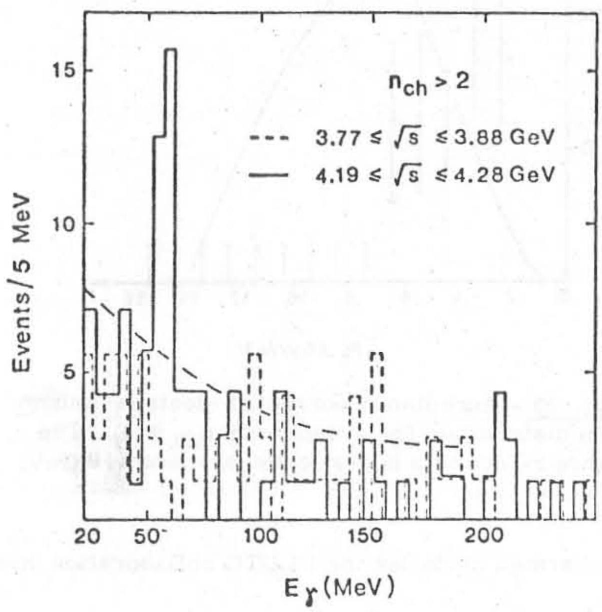


Fig. 30 - Origin of mass peaks in the recoil spectrum against a detected D_+; (a) true peak, (b) (c) kinematic reflections. Typical weights are indicated.

A narrow signal has been detected by the MP^2S^3 collaboration in the inclusive photon spectrum in the 4 GeV region. A preliminary analysis(28) of data collected between 3.8 and 4.3 GeV shows a threshold effect near 4.2 GeV for a γ ray peak having width consistent with the resolution and energy of about 55 MeV. Although the absolute energy calibration could substantially change the central value, yet an instrumental effect seems very unlikely. The excess of events, shown in Fig. 31, is mostly associated with charged multiplicities $n_{ch} \geq 2$ and has a statistical significance of 4 to 5 s.d. Although a $D^* \to D\pi^0$ transition cannot be absolutely ruled out, several alternative hypotheses can be considered such as a γ transition between D^{**} and D^* (if a D^{**} exists) or the expected electromagnetic decay of a vector strange charmed meson F^* into its pseudoscalar partner F, since $F^*_+ \to F_+\gamma$ is expected(27) to be the dominant mode.



In a model-independent way the absence of a large doppler shift and the γ-ray energy allow to kinematically constrain such pairs of particles on a mass scale. The largest Doppler broadening consistent with the data yields minimum values for the upper (U) and lower (L) members of the pair :

$$\begin{aligned} m_U &= 2.08 \text{ GeV}, \\ m_L &= 2.02 \text{ GeV}, \end{aligned} \qquad \text{(for } U\bar{U} \text{ production)}$$

$$\begin{aligned} m_U &= 2.11 \text{ GeV}, \\ m_L &= 2.05 \text{ GeV}. \end{aligned} \qquad \text{(for } U\bar{L} \text{ production)} \tag{24}$$

Fig. 31 - Inclusive photon spectrum associated with charged multiplicities $n_{ch} \geq 2$ in two different c.m. energy intervals.

6.2. - Charm production at DORIS.

The DASP collaboration has found evidence(29) for final states containing one electron and hadrons in the c.m. energy range between 4 and 4.2 GeV. Mixed electron-hadron final states may either arise from the decay of heavy leptons :

$$e^+e^- \to L\bar{L}, \quad L \to \bar{e}\,\nu_e\,\bar{\nu}_L, \quad L \to \nu_L + \text{hadrons} \tag{25}$$

or from the weak leptonic or semileptonic decay of a new hadron, inhibited to decay by the strong and electromagnetic interaction and pair produced in e^+e^- annihilations :

$$e^+e^- \to H\bar{H}, \quad H \to e\,\bar{\nu}_e, \quad H \to e\,\bar{\nu}_e + \text{hadrons} .$$

After all cuts 28 events remain, with conventional sources possibly explaining only 7 events.

The charged multiplicity (including the electron and at least one hadron track), shown in Fig. 32, is considerably higher than what expected for the decay of a sequential heavy lepton. Al so the electron momentum distribution, shown in Fig. 33, is in disagreement with the heavy lepton hypothesis. Semileptonic decays of a meson with a new quantum number could account on the other hand for low-momentum electrons. From the data the mass of such a new hadron should lie between 1.8 and 2.1 GeV.

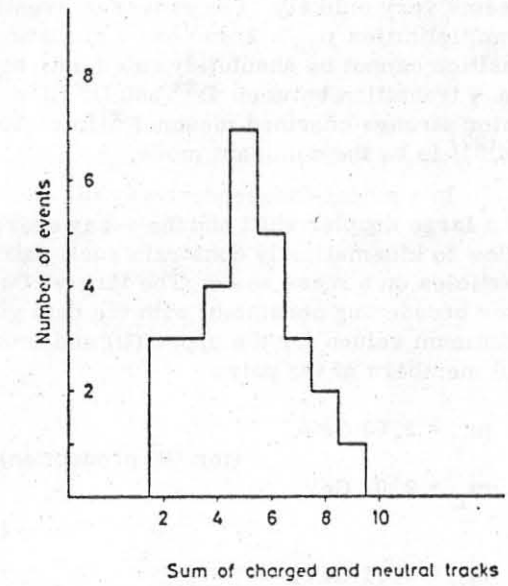


Fig. 32 - Observed number of tracks per event for e + hadrons final states.

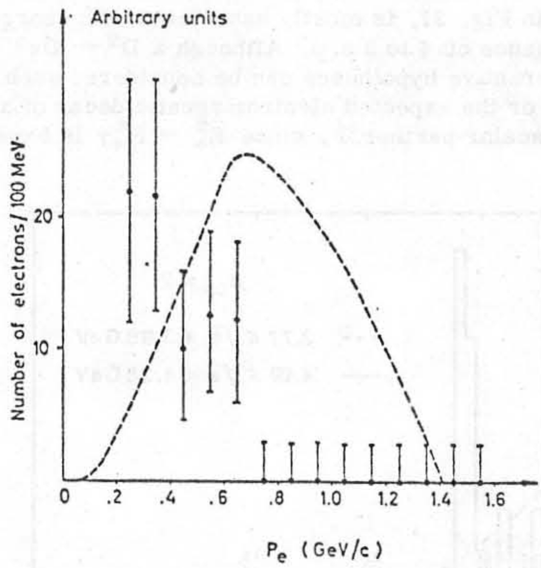


Fig. 33 - Acceptance corrected electron momentum distribution for events with $n_{ch} \geq 4$. The curve refers to a heavy lepton of mass 1.9 GeV.

In a search for semileptonic decays of charmed particles the PLUTO collaboration has found evidence(21) for events of the type

$$e^+e^- \rightarrow e K^o_S + X \tag{27}$$

in a sample of events in the 4-4.3 GeV c.m. energy range. Two particle invariant mass distributions are shown in Fig 34 (a, b, c). A clear signal from the decay $K^o_S \rightarrow \pi^+\pi^-$ is observed at all energies. A search for electrons in this event sample is shown in Fig. 34 (d, e, f) as electron/hadron ratio as a function of the associated two-particle invariant mass. At the K^o mass a statistically significant enhancement above background is seen for the 4-4.3 GeV region (fig. 34e) indicating a strong e-K^o correlation. No such signal is observed either at 3.6 or at 4.4 GeV.

The momentum distribution of the electrons for events at 4.1 GeV is shown in Fig. 35a, the charged multiplicity for these K^oe events is shown in Fig. 35b. The two distributions are very similar to the electron-inclusive data of Figs. 32 and 33. Assuming associated production the data are strongly suggestive of a weak decay into strange final states of a particle with mass between 1.8 and 2.0 GeV.

6.3. - Cross sections.

The cross sections for the production of charmed final states show, whenever available in an energy-dependent form, a threshold behaviour which is similar, as expected, to the discontinuity in R with a peaking around 4.03 GeV.

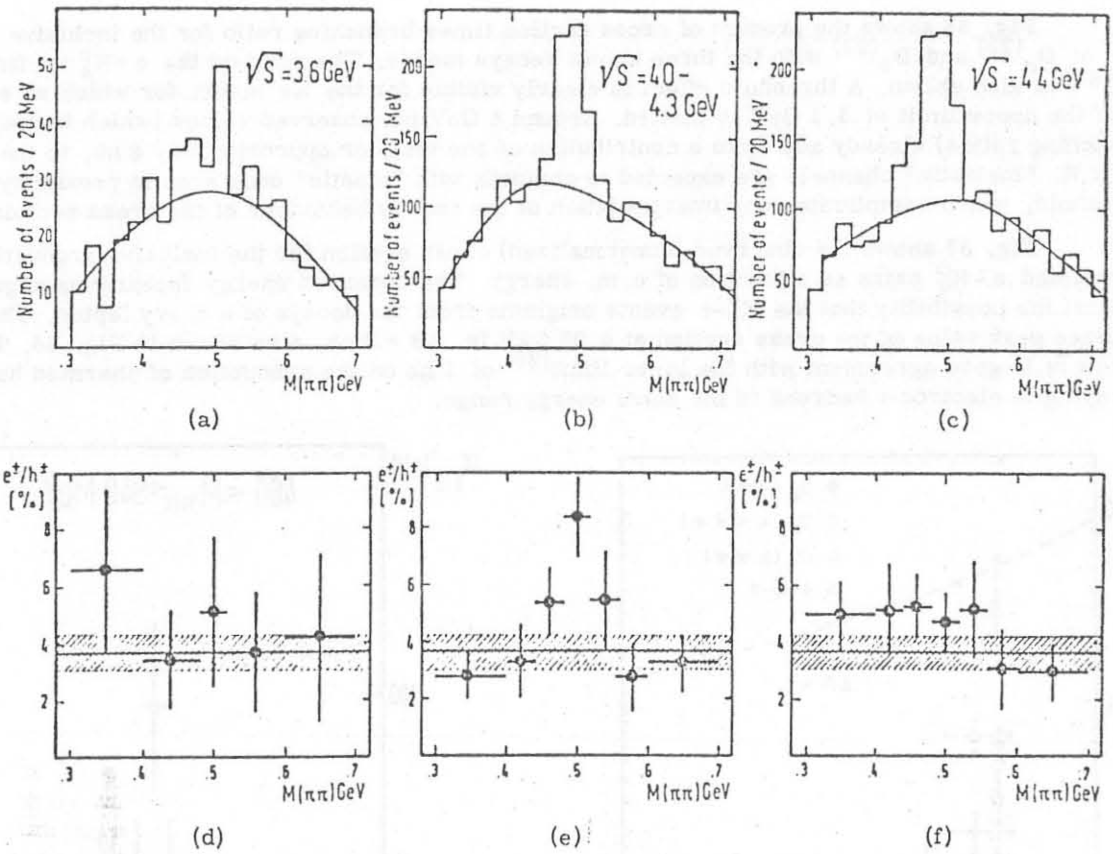


Fig. 34 - Upper histograms : invariant mass distributions of selected π-π pairs with hand-drawn background curves. Lower histograms : e/hadron ratio associated with the π-π pairs ; the shaded area is the background from a random sample of multiprong events.

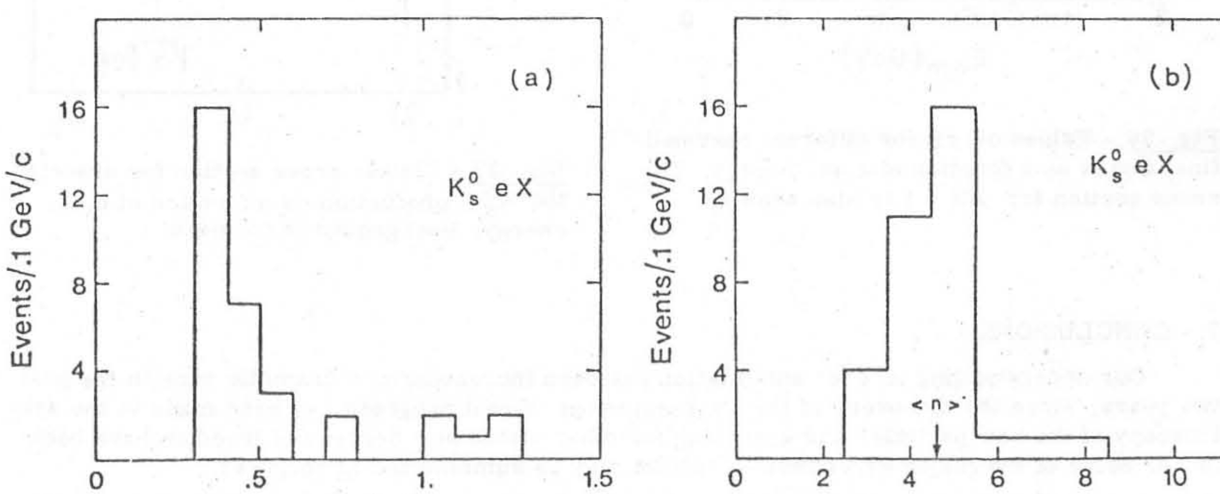


Fig. 35 - (a) Electron momentum distributions for K^0e events at 4.1 GeV c.m. energy. (b) Charged multiplicity of the K^0e events. A 2.5 average charged multiplicity is associated to the K^0e system.

Fig. 36 shows the product of cross section times branching ratio for the inclusive production of D_o[22] and D_+[23] with the three known decays modes. The point on the $e + K_s^o + x$ final states[31] is also shown. A threshold effect is clearly visible for the $K\pi$ mode, for which an estimate of the upper limit at 3.1 GeV is plotted. Around 4 GeV the observed values (which include the branching ratios) already add up to a contribution of one unit, or approximately 6 nb, to the increase of R. "Inelastic" channels are expected to compete with "elastic" ones even in proximity of the threshold, which complicates any interpretation of the energy behaviour of the cross section.

Fig. 37 shows the observed (unnormalized) cross section for the inclusive production of correlated $e - K_s^o$ pairs as a function of c.m. energy. The observed energy dependence argues against the possibility that the K^o-e events originate from the decays of a heavy lepton. The normalized peak value of the cross section at 4.05 GeV is σB = 3 nb, also shown in Fig. 36. This result is in good agreement with the lower limit[29] of 1 nb on the production of charmed hadrons decaying to electron + hadrons in the same energy range.

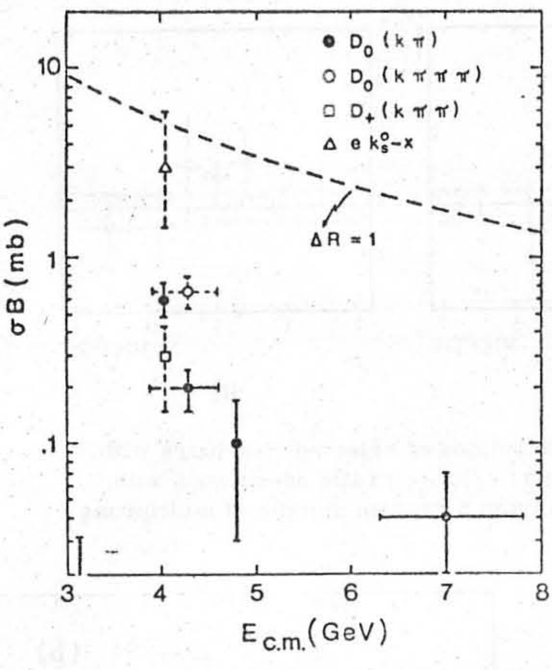


Fig. 36 - Values of σB for different charmed final states as a function of c.m. energy. The cross section for ΔR = 1 is also shown.

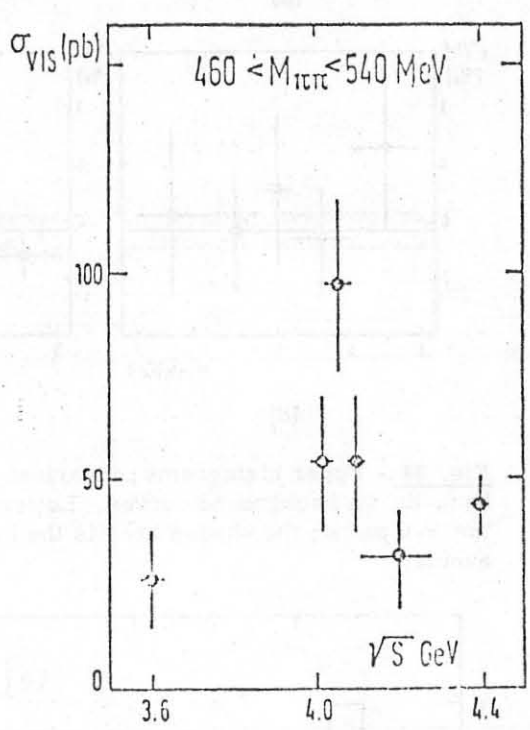


Fig. 37 - Visible cross section for associated K_s^o e production as a function of c.m. energy. Background is included.

7. - CONCLUSIONS. -

Our understanding of e^+e^- annihilation has been increasing at a dramatic pace in the past two years, since the discovery of the ψ resonances. Great progress has been made in the spectroscopy of the new particles and searching for other states new degrees of freedom have been found. Some of the major experimental results may be summarized as follows :

a) In the SPEAR energy range no other narrow objects have been found and rather stringent limits have been set for the production of narrow resonances wich couple directly to the photon.
b) Between the two scaling regions in R the transition region is being resolved in a complicated structure with several broad enhancements.
c) Radiative decays of the ψ'(3864) have led to the discovery of at least three, more likely four, C-even states with masses between 3.40 and 3.55 GeV. A possible fifth state has been obser-

ved at DORIS with mass of 2.85 GeV decaying to two photons. The present spectrum of states is consistent with the number of states expected from the hypothesis of one new quark bound to its antiquark.

d) The narrow states discovered above 4 GeV with neutral $K\pi$, $K\pi\pi\pi$ decays and charged $K\pi\pi$ exotic decay have the properties expected for mesons carrying the new quantum number. From the comparison of theory and data one is led to the conclusion that they correspond to the predicted charmed pseudoscalar isodoublet $D_+ - D_o$. Moreover their hyperfine $D^*_+ - D^*_o$ partners have also been found.
In the same energy region the signature of semileptonic decays of charmed mesons has also been observed at DORIS.

e) Additional evidence has been produced about a new heavy lepton with a mass between 1.8 and 2 GeV decaying to ordinary leptons with neutrinos.

Altogether the rise in R to a value around 5, or perhaps a little larger, can be understood as due to the production of a new charged heavy lepton plus the manifestation of a new coloured quark with charge 2/3.

Asymptotically free theories predict, for energies sufficiently larger than the masses of the quarks that can be excited:

$$R(W) \rightarrow \sum_i Q_i^2 \left[1 + O(\alpha_s(W))\right] , \qquad (28)$$

where the limit is approached from above and α_s is the analog of α in the coulomb part of the quark-quark potential(32). The correction term can be estimated by comparing the data in the first scaling region with the value R = 2 from the u, d and s quarks in the coloured quark model. In the second scaling region we then espect:

$$R(W) \rightarrow \sum_{u,d,s,c} Q^2(1 + O(\alpha_s)) = \frac{10}{3}(1 + O(\alpha_s)) \ . \qquad (29)$$

Adding 25% to the hadronic part of R to account for the approach to the constant limiting value as $W \rightarrow \infty$ from above gives about 4. If a new heavy lepton is being produced, then the observed value of R is raised to about 5. In this scheme, with a total of six leptons (e, ν_e, μ, ν_μ, L, ν_L), the fundamental quark-lepton symmetry would require the existence of new quarks which at present energies are not allowed by the value of R. This could imply that exciting new physics is "postponed" until yet higher energies are reached.

REFERENCES AND FOOTNOTES. -

(1) - G. Zweig, CERN Th 401, Th 412 (1964); J. Iizuka, Suppl. Prog. Theor. Phys. 37, 21 (1966).

(2) - D.C. Hom et al., Phys. Rev. Letters 36, 1236 (1976); D. Eartly et al., Phys. Rev. Letters 36, 1355 (1976).

(3) - Members of the MP^2S^3 collaboration: Maryland: D.H. Badtke, B.A. Barnett, L.H. Jones, G.T. Zorn; Pavia: M. Cavalli Sforza, G. Goggi, F.S. Impellizzeri, M. Livan, F. Pastore, B. Rossini; Princeton: D.G. Aschman, D.G. Coyne, D.E. Groom, G.K. O'Neill, H.F.W. Sadrozinski, K.A. Shinsky; S. Diego: C.J. Biddick, T.H. Burnett, G.E. Masek, E.S. Miller, J.G. Smith, J.P. Stronski, M.K. Sullivan, W. Vernon; Stanford: E.B. Hughes, R.L. Ford, E. Hilger, R. Hofstadter, T.W. Martin, L.H. O'Neill, J.W. Simpson; SLAC: L.P. Keller, D.E. Lyon.

(4) - Maryland-Pavia-Princeton-San Diego-SLAC collaboration, paper submitted to the Tbilisi Conference (1976).

(5) - R. Schwitters, talk given at the "Topical Meeting on Lepton Interactions and New Particles", Trieste (1976); Report IC/76/79 (1976).
(6) - Maryland-Pavia-Princeton-San Diego-Stanford-SLAC collaboration, paper submitted to the Tbilisi Conference (1976).
(7) - V. Lüth, paper presented at the Intern. Neutrino Conf., Aachen (1976); SLAC-PUB 1789 (1976).
(8) - G. W. Buschorn, talk given at the "Topical Meeting on Lepton Interactions and New Particles", Trieste (1976); Report IC/76/79 (1976).
(9) - M. S. Chanowitz and F. J. Gilman, SLAC-PUB 1746 (1976).
(10) - Two pseudoscalar have $J^{PC} = 0^{++}, 1^{--}, 2^{++}$, etc. If produced in a γ transition from the ψ', than $J^{PC} = (\text{even})^{++}$. For a $\pi^+\pi^-$ system in this case I = 0, 2; for a K^+K^- system on the other hand I = 0, 1.
(11) - W. Bartel et al., Proceedings of the 2nd Intern. Conf. on New Results in High Energy Physics, Vanderbilt (1976).
(12) - D. Schmitz, DASP collaboration, invited talk at the Intern. Neutrino Conf., Aachen (1976).
(13) - J. Siegriest et al., Phys. Rev. Letters 36, 700 (1976).
(14) - The lowest $^3D_1$ state, having a vanishing wave function at the origin, presumably has a very small coupling to the photon. The next $^3D_1$ should mix more with the $3\ ^3S_1$ state through charmed meson pairs; the small $\psi(4414)$ is then probably a radially excited D-state with some $3\ ^3S_1$ mixing.
(15) - M. L. Perl et al., Phys. Rev. Letters 35, 1489 (1975); Phys. Letters 63B, 466 (1976).
(16) - M. Cavalli-Sforza et al., Phys. Rev. Letters 36, 558 (1976); M. Cavalli-Sforza and G. Goggi, talk presented at the Intern. Meeting on Storage Ring Physics, Flaine (1976), and Report INFN/AE-76/3 (1976); MP^2 collaboration, T. Atwood et al., paper submitted to the Tbilisi Conference (1976); Note that a different evaluation of the QED background reduces the cross section and the leptonic ratio by about 30%.
(17) - Two-body $1-\nu$ decays can occur only for vector mesons, since helicity conservation in the weak decay of a pseudoscalar object would suppress the $e\nu$ mode with respect to the $\mu\nu$ mode by a factor $(m_e/m_\mu)^2$, thus suppressing the $e\mu$ signal.
(18) - $\varrho = (p - 0.65)/(p_{max} - 0.65)$ is defined so that momentum spectra at different energies can be displayed between 0 and 1 independent of $E_{c.m.}$
(19) - PLUTO collaboration, J. Burmester et al., paper submitted to the Tbilisi Conference (1976).
(20) - G. A. Snow, Phys. Rev. Letters 36, 766 (1976).
(21) - M. B. Einhorn and C. Quigg, Phys. Rev. D12, 2015 (1975).
(22) - G. Goldhaber et al., Phys. Rev. Letters 37, 255 (1976).
(23) - I. Peruzzi et al., Phys. Rev. Letters 37, 569 (1976).
(24) - If the $K\pi\pi$ peak were associated to a strange-meson resonance, the corresponding isospin would have to be 3/2 or 5/2 and doubly-charged decay modes should than be observable. On the other hand for charmed particles decays the favoured $\Delta C = \Delta S$ transition implies, for instance, that a D^+ meson decay to a system with positive charge and S = 1, which is exotic.
(25) - A. De Rojula, H. Georgi and S. L. Glashow, Phys. Rev. D12, 147 (1975).
(26) - A. De Rojula, H. Georgi and S. L. Glashow, Phys. Rev. Letters 37, 398 (1976).
(27) - A. D. Rojula, talk given at the Neutrino Phys. Meeting, Aachen (1976); HUTP-76/168 (1976).
(28) - Maryland-Pavia-Princeton-San Diego-Stanford-SLAC collaboration, paper submitted to the Tbilisi Conference (1976).
(29) - W. Braunschweig et al., Phys. Letters 63B, 471 (1976).
(30) - Y. S. Tsai, Phys. Rev. D4, 2821 (1971).
(31) - J. Burmester et al. (PLUTO collaboration), contributed paper to the Tbilisi Conference (1976); DESY-76/50 (1976).
(32) - See f. i.: G. Altarelli, Proceedings Ecole d'èté de physique des particules, Gif-sur-Yvette (1975).