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Review of e^+e^- Reactions

by

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REVIEW OF e^+e^- REACTIONS.*

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Abstract

Recent experimental results on e^+e^- reactions are reviewed, in particular the properties of the heavy lepton τ and the $\Upsilon(9.46)$ and $\Upsilon'(10.02)$ mesons. Also the total hadronic cross section and the 2-jet structure of annihilation events are discussed.

1. Introduction

I have been asked to give an one hour experimental review of e^+e^- reactions. This is not an easy task, since the field of e^+e^- reactions has been extremely fruitful in the last four years and in particular in the last year. Therefore I have to be highly selective. I will limit myself to some of the most important new results obtained in the last year. For a more complete survey of the field I refer to the summary reports at the Tokyo Conference[1-3] and to refs. 4 and 5.

The biggest progress made last year was first in finally establishing the existence and the weak decay properties of the heavy lepton τ. Secondly, the Υ and Υ' mesons have been observed at DORIS, which provided a first promising look into the Υ and b state spectroscopy. We also have some new information on total cross sections and jet structure. Both the reaction dynamics and the new particle spectroscopy can be understood in terms of quark-parton and quarkonium models, respectively.

We report in section 2 on the establishment of the τ as a heavy lepton. In section 3 some aspects of the reaction dynamics, i.e. the total cross section, the charged multiplitícy, the division of energy among different particle species and the 2-jet structure are discussed. In sections 4 and 5

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we present recent results from DORIS on charm and charmonium spectroscopy and on the new heavy mesons $\Upsilon(9.46)$ and $\Upsilon'(10.02)$.

2. The Heavy Lepton τ

2.1 Introduction

At the 1977 Hamburg conference[6-8] there was growing evidence that the τ is a sequential heavy lepton. However, a number of crucial questions were not definitely answered, in particular:

- What is the exact mass of the τ?
- Is the τ really a spin 1/2 lepton not related to charm*?
- Are the weak interactions of the τ the same as those of the electron and muon? I.e. do both the weak leptonic and the weak hadronic currents in τ decay have the expected V,A structure?

In the following I will address the above questions. New data have been reported from the following experiments: DASP[9], DESY-Heidelberg[10], PLUTO[11,12], DELCO[13,14], MARK I[15-17], MARK I with lead glass wall[18], MARK II[19].

2.2 The τ production cross section

An accurate measurement of the τ production cross section close to threshold can be used to pin down both the spin and the mass of the τ.
Last fall the DASP collaboration[9] reported a measurement of the 2-prong cross section for the reaction

$$e^+e^- \to e^\pm + \text{nonshowering track} + n \text{ photons } (n \geq 0) \qquad (1)$$

which is shown in Fig. 1.a. They found 7 events at $E_{CM} = M_{\psi'}$, i.e. below the charm threshold (after subtracting 3 ± 0.5 background events). From a study of their multiprong events with electron they were able to show that the feeddown of leptonic charmed particle decays into reaction (1) above charm threshold is very small. Hence the data can be attributed to the process

$$e^+e^- \to \tau^\pm \tau^\mp, \quad \tau^\mp \to \text{nonshowering track} + \nu + n\gamma (n \geq 0), \quad \tau^\pm \to e^\pm \nu\nu$$

* This question was discussed by J. Kirkby at the Hamburg Conference, loco cit.(ref. 6).

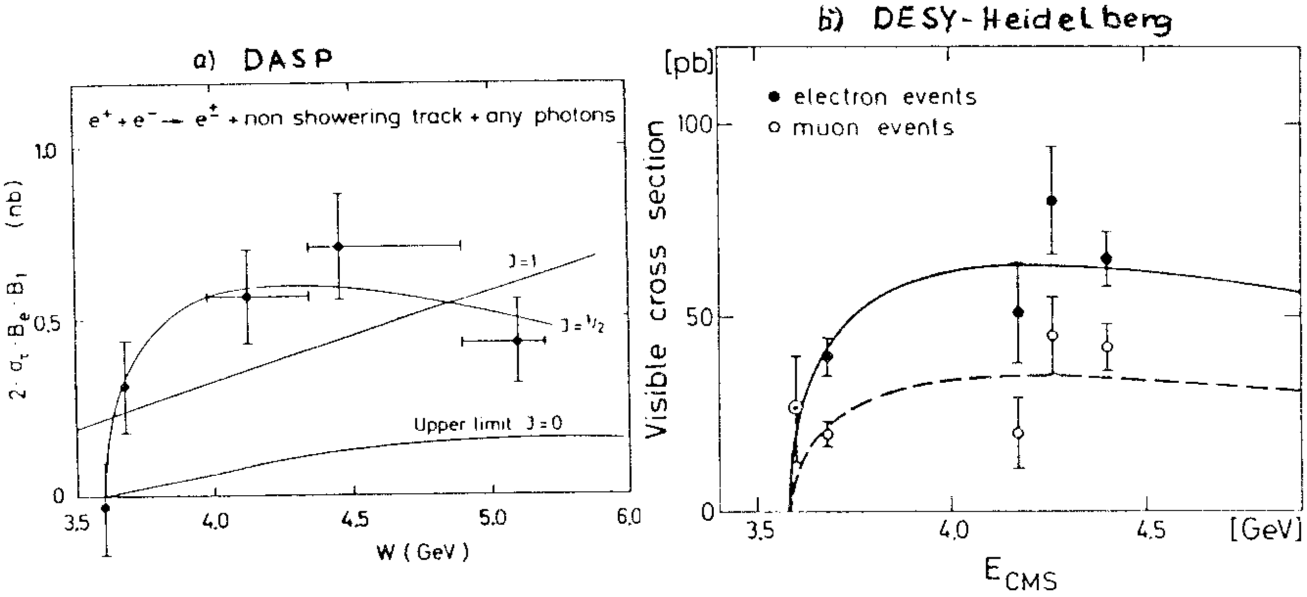

Fig. 1 a) Cross section for 2 prong events with electron plus any number of photons from DASP [9]. The curve labelled J = 1/2 is the QED cross section for a pair of pointlike spin 1/2 particles. For details on the other curves see ref. 9. b) Visible cross section for 2 prongs with electron and muon, respectively, from ref. 10. The curves refer to the spin 1/2 case.

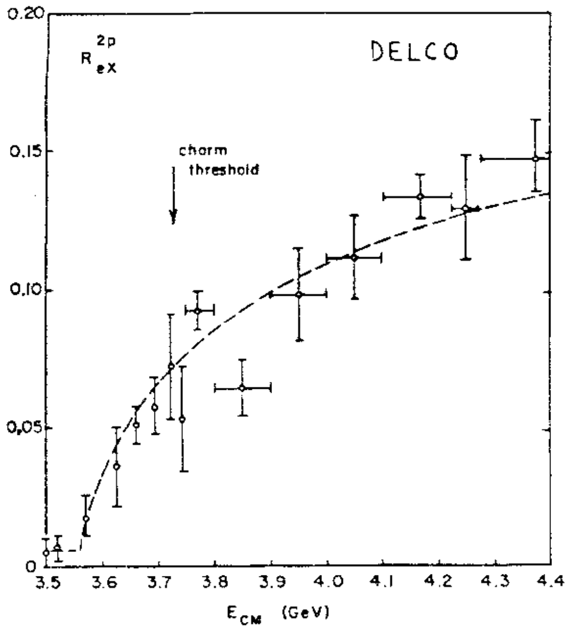

Fig. 2) The ratio $R^{2p}_{ex} = \sigma(e^+e^- \to e^\pm x)/\sigma(e^+e^- \to \mu^+\mu^-)$ from the DELCO group [14]. The curve is a QED calculation (spin 1/2) for $e^+e^- \to \tau^+\tau^-$ including radiative effects.

A fit assuming the production of a pair of pointlike spin 1/2 particles according to QED describes the data well and yields $M_\tau = 1.807 \pm 0.020$ GeV. In contrast the assumption of spin 0 or 1 for the produced particles does not reproduce the data, in particular when higher energy data from SLAC[13] are included (see curves in Fig. 1a)*. Similar results were recently obtained by the DESY-Heidelberg group[10], who measured the cross section for the reactions

$$e^+e^- \rightarrow \begin{matrix} e^\pm \\ \mu^\pm \end{matrix} + 1 \text{ charged track} + \text{no photon} + \text{missing energy} \qquad (2)$$

shown in Fig. 1b. They have 125 events below charm threshold.

A fit to a spin 1/2 pair production cross section yields**

$$M_\tau = 1.790 \begin{matrix} + 0.007 \\ - 0.010 \end{matrix} \text{ GeV.}$$

Shortly after the DASP collaboration the DELCO group at SPEAR[13] reported a measurement of reaction (1) from threshold to 7.4 GeV. Fig. 2 shows their cross section divided by $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$[14]. The dashed curve is from a QED fit as for the DASP data (spin 1/2), but including the changes due to radiative effects. They obtain a τ mass value of

$$M_\tau = 1.782 \begin{matrix} + 0.003 \\ - 0.004 \end{matrix} \text{ GeV.}$$

In summary, we now have accurate measurements of the τ mass. The observation of τ events below the charm threshold demonstrates unambiguously that the τ is unrelated to charmed particles. The τ production cross section follows precisely the QED cross section for the production of a pointlike spin 1/2 lepton pair.

2.3 Leptonic τ Decays

New data are available on the branching ratio $B(\tau \rightarrow e\,\nu\nu)$ and on the V,A structure of the leptonic τ decay current. From the standard model of τ decay one expects that $B(\tau \rightarrow e\,\nu_\tau \nu_e) \approx 20\,\%$[17]. A detailed calculation yields $B(\tau \rightarrow e\,\nu_\tau\,\nu_e) = 16.8\,\%$[20]. The new results are as follows:

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* Evidence against a spin 0 assignment was first presented by the PLUTO group (J. Burmester et al., Phys.Lett. 68B (1977)297.

** In this fit a V-A coupling of the τ was assumed. The mass values from DASP and DELCO are insensitive to the assumptions about the τ coupling.

	$B(\tau \to e\nu\nu)$
DASP [9]	18.2 ± 3.1 %
DELCO [13,14]	16.0 ± 1.3 %

The systematic uncertainties are included in the errors. A combined fit to all τ data yields an average of $B(\tau \to e\,\nu\nu) = 18.3 \pm 1.9$ % [2,17] in agreement with theory. The same fit gives $B(\tau \to \mu\nu\nu)$ / $B(\tau \to e\nu\nu) = 1.08 \pm 0.17$ as compared to the predicted value of 0.973[20].

The V,A structure of the leptonic current in τ decay can be derived from the shape of the charged lepton momentum spectrum. The DELCO group has presented conclusive data on this question. For a V-A current one expects a hard electron spectrum as shown in Fig. 3.a. The expected spectrum is characterized by a

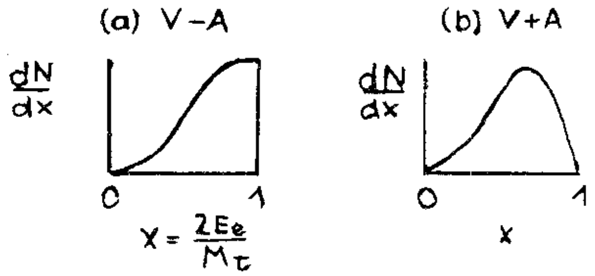


Fig. 3: Expected electron momentum spectra from a stationary $\tau \to e\ \nu\nu$ decay for
a) V-A and
b) V+A coupling

Michel parameter of 0.75, which reduces to 0.53, when the DELCO group includes radiative effects. The spectrum from a V+A coupling is softer (Fig. 3.b), corresponding to a Michel parameter of $\rho = 0$ (without rad. corr.) and $\rho = -0.15$ (with rad. effects). If the τ decay is not at rest the difference between the two spectra is reduced. Fig. 4 shows the measured spectrum. The full curve re-

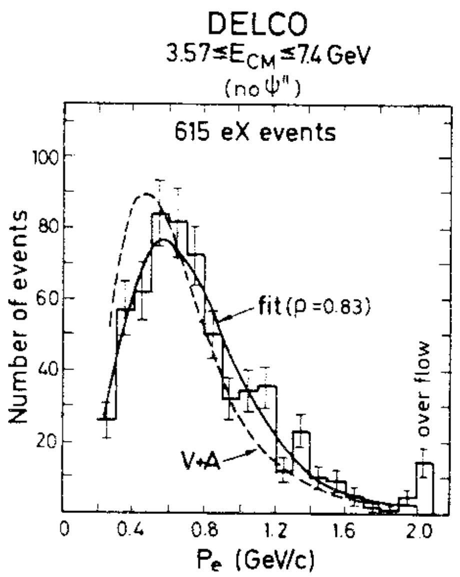
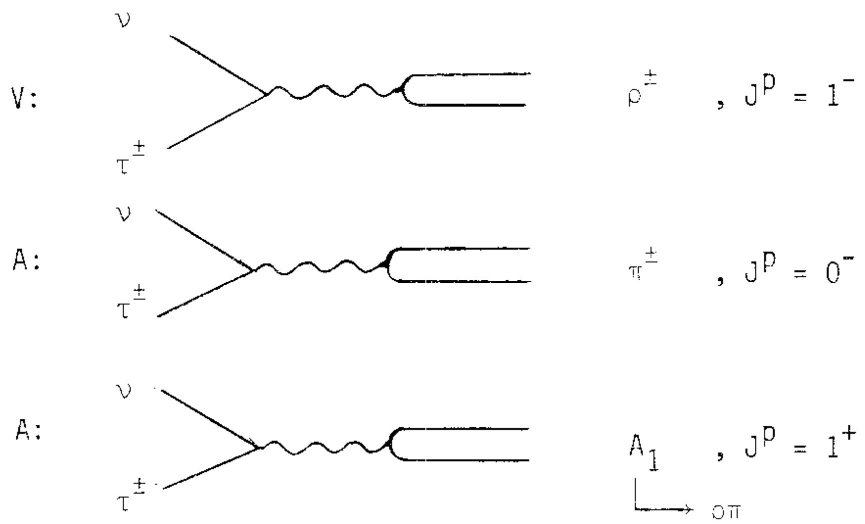


Fig. 4) Electron momentum spectrum of 2 prongs with electron from DELCO[14]. The plot shows all 615 events taken in the E_{CM} interval 3.57 - 7.4 GeV, but excluding the ψ'' resonance. The full curve is from a fit which leaves the Michel parameter free. The dashed curve gives the spectrum shape expected for a pure V+A coupling at the τ vertex. This curve includes the effects of radiation.

sults from a fit which leaves ρ free. The result is $\rho = 0.83 \pm 0.12$ (statist.) $\pm$ 0.15 (syst.) with a $\chi^2 = 25.3$ for 17 degrees of freedom. This is consistent with the value expected for a V-A coupling (though high by 1.7σ). The dashed curve shows the spectrum shape expected for a V+A coupling yielding a $\chi^2 = 83.9$ for 18 df. Thus a V+A coupling is ruled out by 5.7σ. Pure V or A couplings are disfavored by $\sim 3\sigma$. Hence we have good evidence that the leptonic τ decay current has a standard V-A structure.

2.4 Hadronic τ Decays

The evidence for a V-A coupling at the τ vertex leads to the immediate question: Does the leptonic τ decay current couple to both the weak hadronic vector and axial vector currents? If yes, one expects decays of the kind:



The $\tau \to \rho\nu$ decay - involving the hadronic vector current - has been seen by the DASP collaboration[6]. The experimental branching ratio of 24 ± 9 % agrees with theory. The decay mode has also been recently observed in the MARK II detector[19].

The PLUTO group has presented evidence for the decay $\tau \to \rho\pi\nu$[11)*]. The $\rho\pi$ system is dominantly in a $J^P = 1^+$ ($\ell = 0$) state (Ref. 21 and 22). The observed decay rate of 10.4 ± 2.4 % (statist.) ± 2 % (syst.) matches the expected value for the decay $\tau \to A_1\nu$ of $\sim$9%[20]. Hence we have good evidence for the coupling to the $J^P = 1^+$ axial vector hadronic current.

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* The decay $\tau \to \nu 3\pi$ has been also observed by the SLAC-LBL group[16].

The decay $\tau \to \pi\nu$ was not established a year ago. The DASP result[6] was consistent with 0 and 2σ below the expected value of 9.5 % [20]. This year four groups have seen the decay mode. The results are given in Table 1. The average value of $B(\tau \to \pi\nu)$ is consistent with the expected value.

Table 1: Results for $B(\tau \to \pi\nu)$

Exp.	Ref.	$B(\tau \to \pi\nu)$ %	statist. errors	syst. errors	measured topology
PLUTO	12	9.0	± 2.9	± 2.5	π + ch + 0γ
DELCO	14	6.0	± 1.6	$^{+1.9}_{-1.2}$	π + e + 0γ
MARK I	17	9.3	± 3.9		π + ch + 0γ
MARK II	19	8.0	± 1.1	± 1.5	π + ch + 0γ
MARK II	19	8.2	± 2.0	± 1.5	π + e + 0γ
average		7.7 ± 1.3 %.			

Other hadronic decay modes are summarized in Refs. 17 and 23.

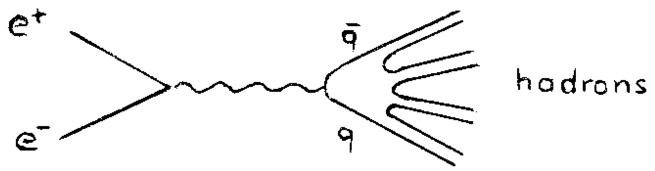
2.5 Conclusions on the τ

1. All experimental evidence is well consistent with the existence of a sequential heavy lepton τ with spin 1/2.
2. We have good evidence that the τ decay proceeds via standard V-A interactions. Both vector and axial vector hadronic final states have been observed.
3. Let me finally mention three open questions, which I could not cover : We need more accurate data on the τ lifetime (present limit $< 3 \cdot 10^{-12}$ sec[14]) and the ν_τ mass (present limit < 250 MeV at 90 % c.l.[13]). The possibility that the τ is an ortholepton (with $\nu_\tau \equiv \nu_e$) rather than a sequential lepton has not yet been ruled out.

3. General Properties of Hadron Production

3.1 Introduction

In this chapter I want to review some of the new data on hadron production with the quark parton model as a guideline. I.e. the annihilation process is thought as the sum of the contributions from diagrams,



where the virtual photon couples to a $q\bar{q}$ pair, which subsequently fragments into hadrons. I want to limit myself to the following topics:

- σ_{tot} (3.2)
- the mean charged multiplicity (3.3)
- which particles carry the energy away (3.4)
- 2 jet structure (3.5).

In order to isolate the contributions from the above diagrams events from two background sources have to be subtracted:

a) all QED processes including $e^+e^- \to \tau^+\tau^-$. (The τ subtraction has presently been done only on part of the data).

b) Two photon exchange processes, which are generally unimportant for $E_{CM} \lesssim 10$ GeV.

3.2 The total hadronic annihilation cross section

Here the quark parton model predicts

$$\sigma_{tot} = 3 \sum_i Q_{q_i}^2 \underbrace{\sigma_{e^+e^- \to q\bar{q}}}_{= \sigma_{e^+e^- \to \mu^+\mu^-} (\sigma_{\mu\mu})} ,$$

where Q_{q_i} is the charge of the quark q_i. We assume that quarks come in three colors. Generally the data are presented in terms of

$$R = \frac{\sigma_{tot}}{\sigma_{\mu\mu}} .$$

Table 2 shows the expected values of R at E_{CM} = 3 and 5 GeV including the contributions from $e^+e^- \to \tau^+\tau^-$ and a QCD correction.

Table 2: Expected contributions to R

Contributions to R	E_{CM} = 3 GeV	E_{CM} = 5 GeV
u,d,s quarks in 3 colors	2	
u,d,s,c quarks in 3 colors		3.33
$e^+e^- \to \tau^+\tau^-$	-	~ 1
QCD correction*	~ 0.3	~ 0.4
total expected R	2.3	4.7

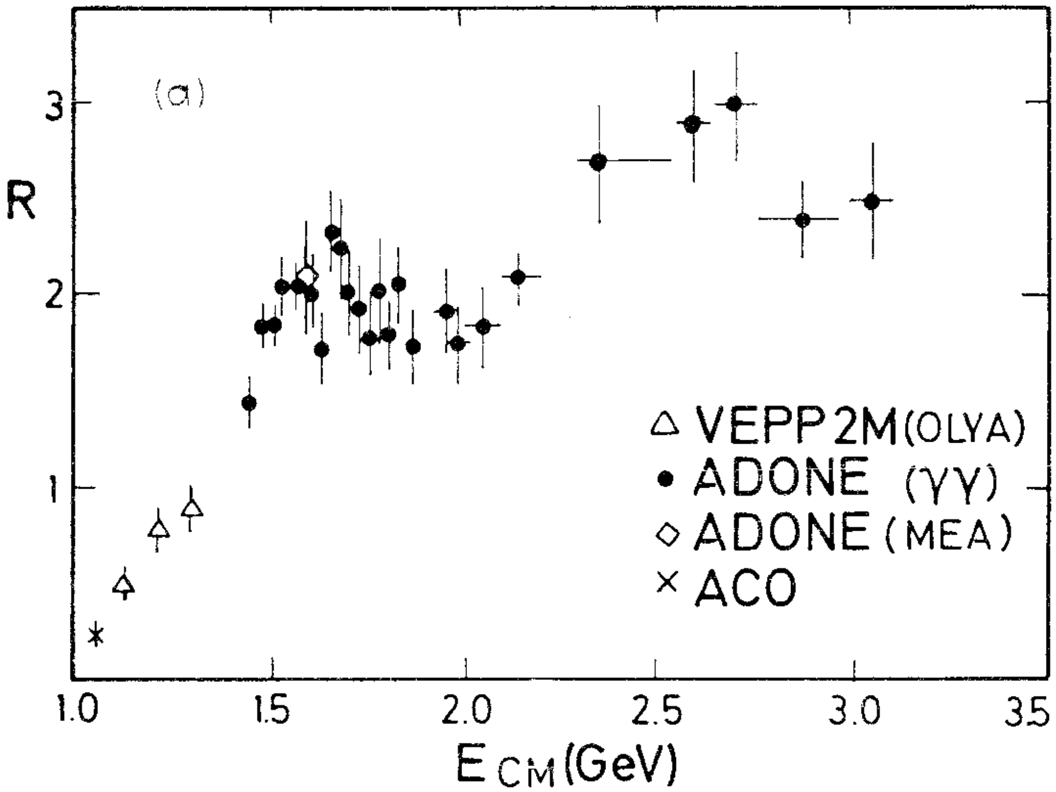
* The QCD correction was computed from the formula
$\Delta R_{QCD} = \sum_i 3Q_{q_i}^2 \cdot 12 / (27 \ln \frac{s}{\Lambda^2})$ (Ref. 24) with Λ = 0.73 GeV.

This year new data on σ_{tot} have been reported from ADONE[25] and DCI[26] (E_{CM} < 3 GeV) and from the DASP[27] and DELCO[14] groups (E_{CM} > 3 GeV). The SLAC-LBL collaboration reanalyzed their data[2].

Fig. 5.a, b show the results on R from ADONE and DCI. The data agree with each other. They reach the quark model value of ~ 2 at $E_{CM} \approx 1.5$ GeV.

The new data on R above 3 GeV are shown in Fig. 6a-c together with the 1977 results from PLUTO (Fig. 6.d). All data include the contributions from $e^+e^- \to \tau^+\tau^-$. The errors shown are statistical. Systematic uncertainties are typically 10-15 % (see error band in Fig. 6.d). The DELCO data are not yet radiatively corrected (apart from the radiative ψ and ψ' tails). Note that radiative corrections tend to enhance peaks and to bring down dips. The net effect depends on the assumed amount of peaking and dipping in the "true" cross section. The curves in Fig. 6a-d represent a handdrawn line through the PLUTO data.
We make the following observations from Fig. 6:

1. All data sets show peaks at 4.05 and 4.4 GeV and a dip at 4.25 GeV.
2. The dip at 4.10 GeV seen by the two DORIS experiments is not present in the SLAC-LBL data. The dip might develop in the DELCO data after radiative corrections have been applied.



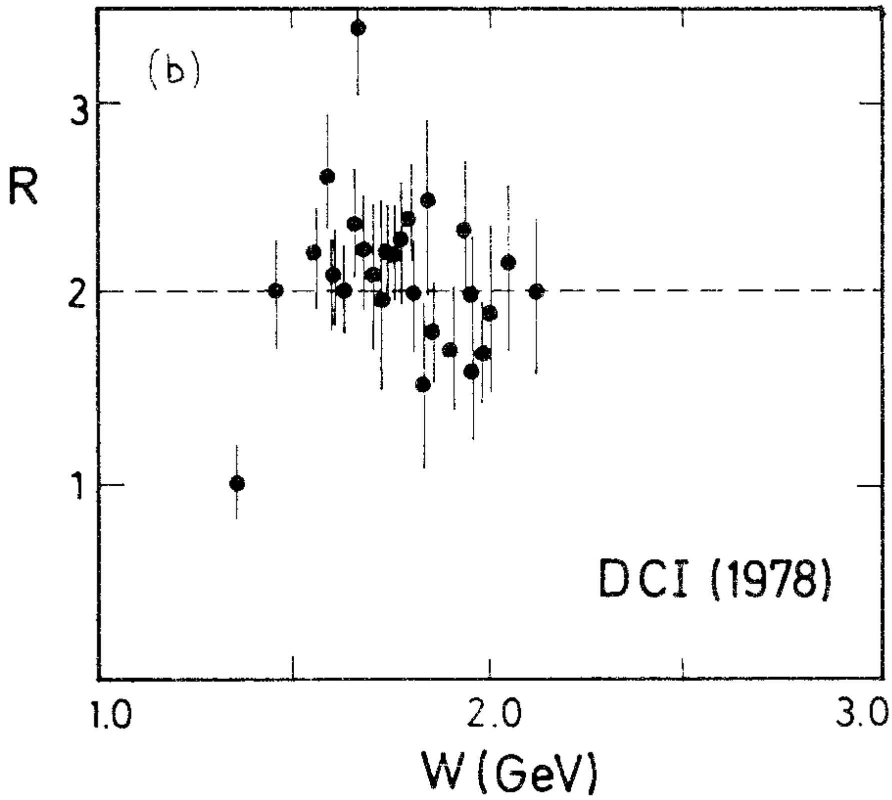


Fig. 5) Results on R from a) ADONE and b) DCI.
In fig. 5a) low energy points from VEPP (Novosibirsk) and ACO (Orsay) are included.

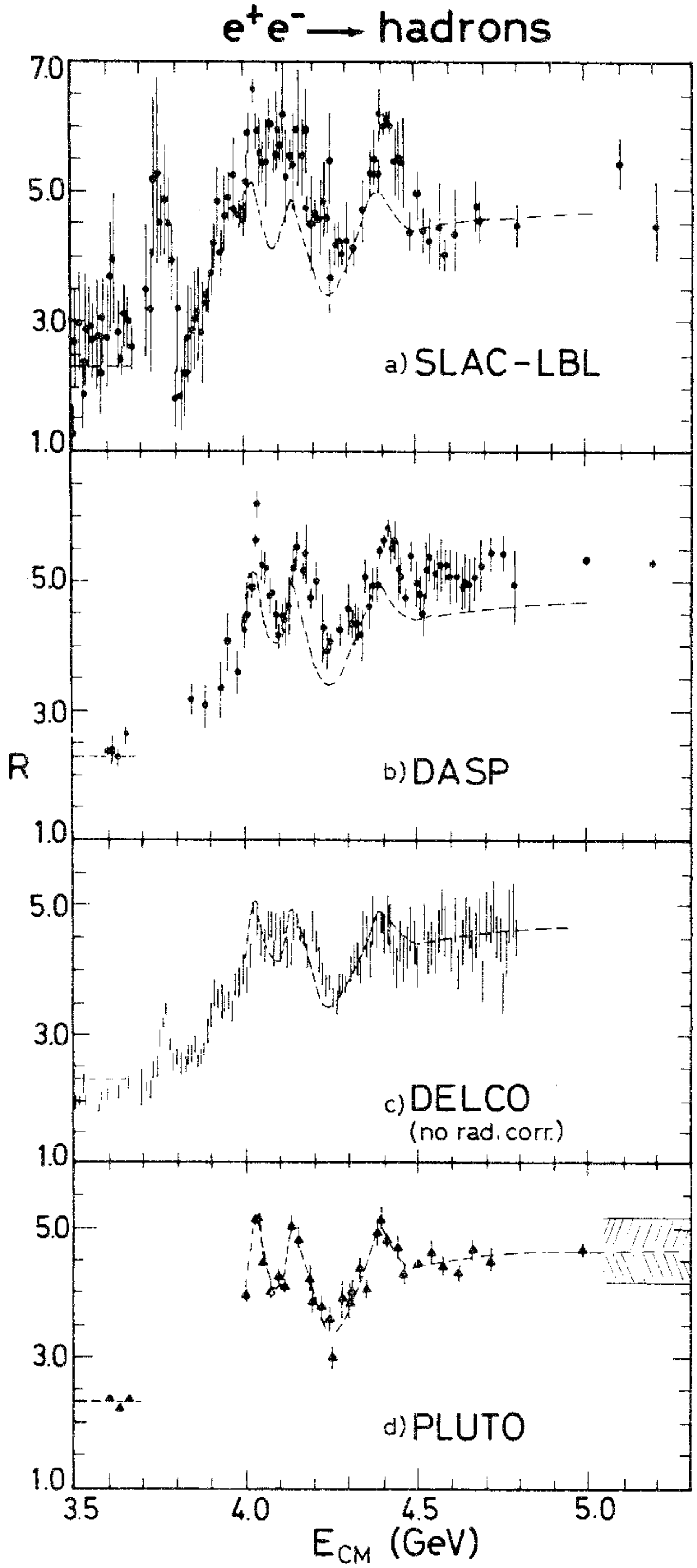


Fig. 6) Results on R (including $e^+e^- \to \tau^+\tau^-$) from four experiments a) SLAC-LBL [2], b) DASP [27], c) DELCO [14], d) PLUTO [28]. The curves represent a handdrawn line through the PLUTO data. The shaded band in fig. 6d) indicates the systematic errors of the PLUTO measurement. The plots shown were compiled by G. Feldman [2].

3. The PLUTO and DELCO results agree quantitatively. These are the two experiments with high detection efficiencies of 80 and 85 %, respectively. *
4. Though there are some statistical discrepancies between the PLUTO/DELCO cross sections on the one hand and the DASP/SLAC-LBL cross sections on the other hand, all data sets are consistent, when the systematic uncertainties are taken into account.
5. Good agreement is found with the quark model predictions of Table 2.

3.3 Mean charged multiplicity $\langle n_{ch} \rangle$

Results on $\langle n_{ch} \rangle$ with and without heavy lepton subtraction are now available from the SLAC-LBL collaboration[29,30] as shown in Fig. 7. The unsubtracted data[30] are indicated by the dashed curve. Heavy lepton events $e^+e^- \to \tau^+\tau^-$ have $\langle n_{ch} \rangle \approx 3$. This is lower than the $\langle n_{ch} \rangle$ value of the purely hadronic events. Hence the heavy lepton subtraction leads to an increase of $\langle n_{ch} \rangle$. Only the subtracted data should be used for comparisons with dynamical models.

3.4 Which particles carry the energy away ?

At the 1975 Stanford Conference the SLAC-LBL group reported that only ~ 50 % of the total energy is carried away by the charged particles $\pi^\pm$, $K^\pm$, $e^\pm$, $\mu^\pm$ and $p,\bar{p}$.[31] This caused speculations about a so called "energy crisis". In the last year new data on particle production became available. I will use these data to analyze which particles carry the remaining energy away. The data include the production rates and energy spectra of π^0 mesons (lead glass wall exp. (LGW)[32]), K^0 mesons (PLUTO[33], SLAC-LBL[34]), η-mesons (DASP[35]), leptons (DASP[9,36], LGW[18,37], DELCO[13,14]), protons (SLAC-LBL[38a], DASP[39]), Lambdas (SLAC-LBL[38a]) and Sigmas[38b].

Let me first give you an impression of the particle spectra. Fig. 8 shows the momentum distributions $d\sigma/dp$ of $\pi^\pm$, $K^\pm$ and $p,\bar{p}$ from DASP[39]. At about 500 MeV, pions are 10 times more frequent than kaons, whereas at 1.5 GeV/c

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* The detection efficiencies of DASP and MARK 1 are 40 % and ∼ 50%, respectively.

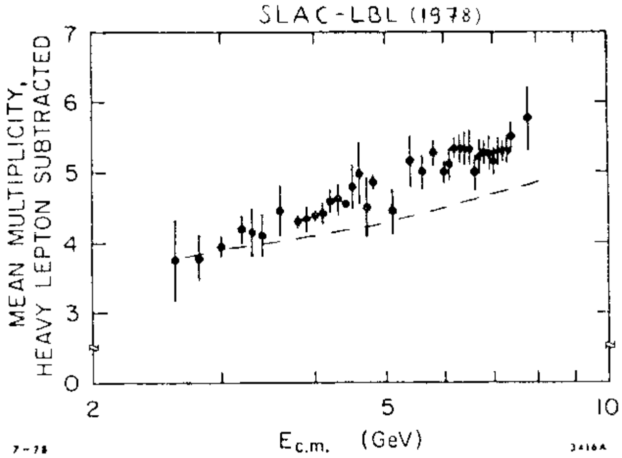

Fig. 7) Mean charged multiplicity after heavy lepton subtraction from ref. 29. The energy dependence of the unsubtracted data [30] is indicated by the dashed line.

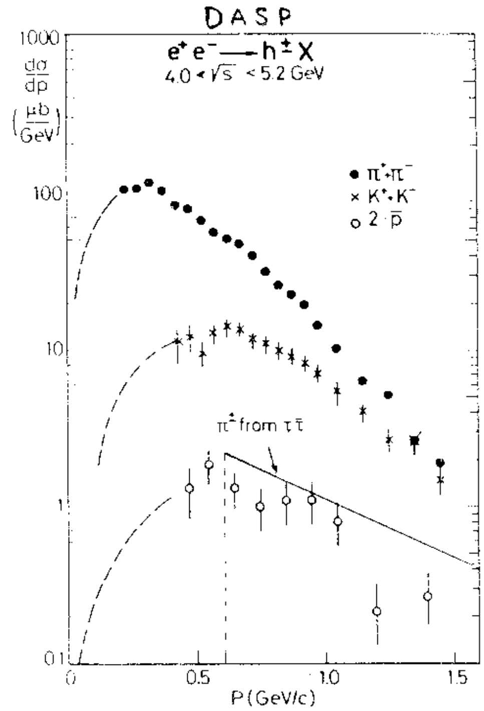

Fig. 8) Inclusive cross sections $d\sigma/dp$ for production of $\pi^+ + \pi^-$ mesons, $K^+ + K^-$ mesons and p, $\bar{p}$ as measured by DASP [39]. The dashed curves show the expected behaviour at small momenta obtained from exponential fits to the invariant cross sections. The full curve shows the estimated contribution of pions from $\tau^+\tau^-$ events.

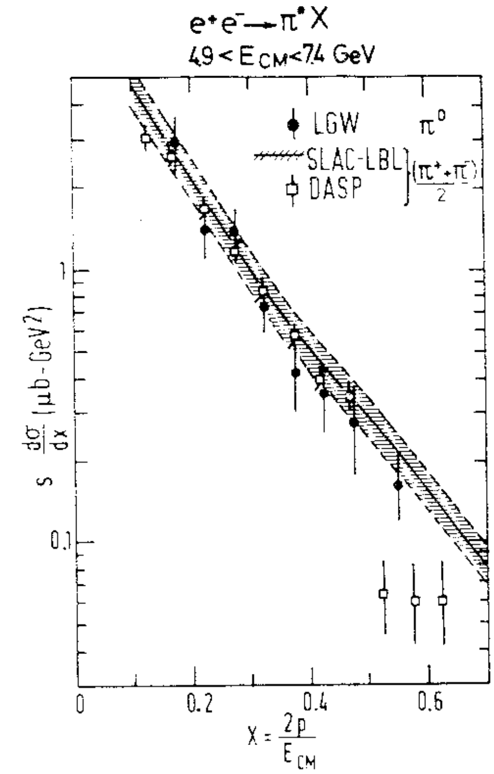

Fig. 9) Inclusive π^0 cross section $s \cdot d\sigma/dx$ from the LGW experiment [32]. The dashed band and the open squares are 1/2 of the sum of π^+ and π^- cross sections from MARK1 and DASP (at E_{CM}= 5 GeV) [39], respectively.

the pions and kaons are produced with about the same rate. Protons are a factor 10 below the kaons. The full line shows the estimated contribution of pions from $\tau^+\tau^-$ events. The heavy lepton contamination becomes more important with increasing pion momentum.

Fig. 9 shows new data on inclusive π^0 production from the LGW experiment [32] (full points). The points are to be compared to half of the $\pi^+ + \pi^-$ rate from MARK 1 (dashed band) and DASP[39] (open squares). The data are in good agreement with the standard assumption

$$N_{\pi^0} = \frac{1}{2}(N_{\pi^+} + N_{\pi^-}) \quad \text{for } 0.1 < x < 0.6.$$

I have used the available data to construct Fig. 10.

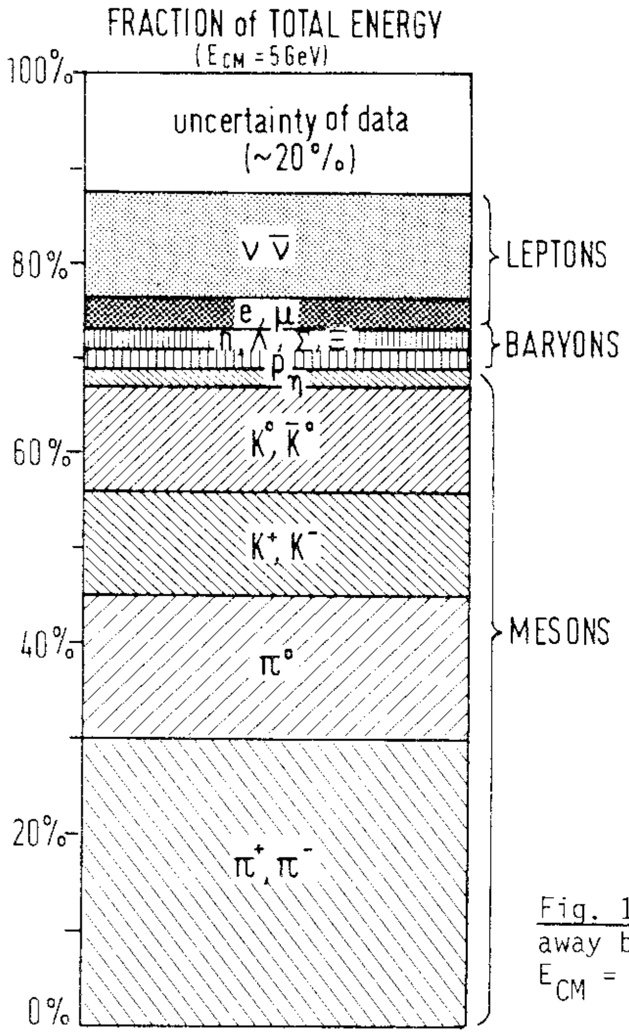

Fig. 10) Fraction of total energy carried away by different particle species (at E_{CM} = 5 GeV).

The π, K and η mesons *) carry away about 70 % of the total energy (at E_{CM} = 5 GeV). Baryons carry only about 5 % **). Leptons (mostly from τ decays) carry about 14 % of the total energy. The sum of all contributions is 88 $\pm$ 20%. This leaves room for some direct photons (not from π^0 or η decays). In summary, the above particles account for the total energy. The 1975 energy crisis arose since at that time the considerable K^0 contribution (partly from charm decays) and the sizeable lepton contribution (largely from τ decays) were not yet known.***

3.5 Two Jet Structure

The occurence of jets in e^+e^- annihilation has been a principal prediction of the quark-parton model : If the hadrons fragment from the two quarks with limited transverse momentum $p_\perp$, then the hadrons should come in two opposite jets. The angular distribution of the jet axis should follow the $q\bar{q}$ angular distribution

$$W(\Theta) \approx 1 + \cos^2\Theta.$$

The first evidence for jets was obtained by the SLAC-LBL collaboration in 1975 [31,40]. They found that the transverse momentum is limited to $p_\perp \sim 350$ MeV/c [41] and that the angular distribution of the jet axis shows the expected behavior for E_{CM} = 7.4 GeV.

In addition to the problem of jet quantum numbers some more general questions remained open :

1) What uncertainties are involved in finding the jet axis ?
2) How is the neutral energy distributed ?
3) How wide are the jets in space ?

The PLUTO collaboration has reported new data up to E_{CM} = 9.4 GeV which are relevant to these questions [42].

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* I have used the 1σ upper limit on the inclusive η production cross section from ref. 35

** The rates of n, Σ^0, Ξ production have been estimated from the proton, Λ and $\Sigma^\pm$ rates.

*** The contribution of τ events to the neutral energy was discussed first by K. Fujikawa and N. Kawamoto (Phys.Rev.Letters 35 (1975) 1560).

3.5.1 Finding the jet axis

The experimental determination of the jet axis suffers from a number of difficulties.

1) The many proposed jet variables[43] lead to slightly different results.
2) As long as the neutral energy is not included, the jet axis determination will be biassed.
3) Acceptance corrections, radiative corrections and heavy lepton subtractions have to be applied on a statistical basis.

The PLUTO group has used two variables to measure the "jettiness" of an event:

a) Sphericity. Here an axis is determined, which minimizes the square of the transverse momenta with respect to the axis. For each event the quantity

$$S = \frac{3}{2} \, \mathrm{Min} \frac{\sum_i p_{\perp i}^2}{\sum_i p_i^2}$$

is computed.

b) Thrust. The thrust axis maximizes the linear longitudinal momentum. One determines for each event the quantity

$$T = \mathrm{Max.} \frac{\sum_i |p_{\parallel i}|}{\sum_i |p_i|}$$

The limiting values of S and T for extreme topologies are [43]

	isotropic event, all momenta equal	pure 2 jet, $p_{\perp i} = 0$
S	1	0
T	1/2	1
1 - T	1/2	0

Fig. 11a shows the mean observed sphericity from charged tracks as a function of energy E_{CM}.* The data sample is restricted to all ≥ 4 prong events with $E_{vis} \geq E_{CM}/2$ where E_{vis} is the detected charged and neutral energy.

* Acceptance and radiative corrections have not yet been applied.

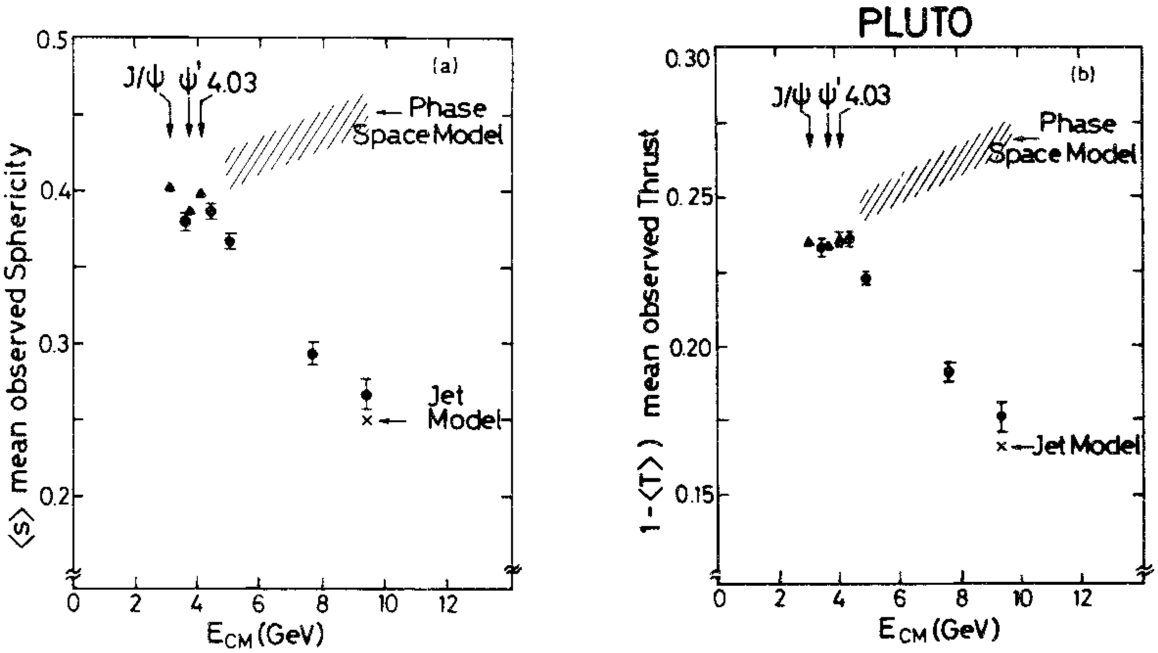


Fig. 11) PLUTO results on jet properties (using events with $\geq$ 4 prongs)[42]. a) mean observed sphericity from charged tracks vs. E_{CM} . b) $1-\langle T\rangle$ vs. E_{CM}, where $\langle T\rangle$ is the mean observed thrust value from charged tracks. The crosses are from the jet model of ref. 44. The hatched bands are from a phase space model.

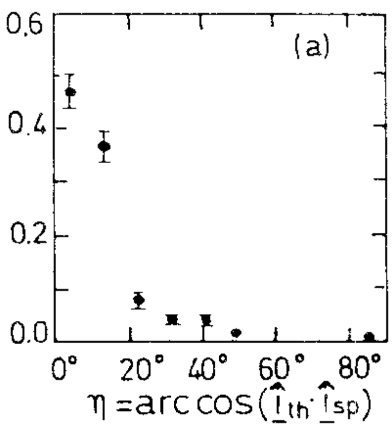


Fig. 12) Distribution of the angle η between the thrust and sphericity axes at 9.4 GeV from PLUTO [42].

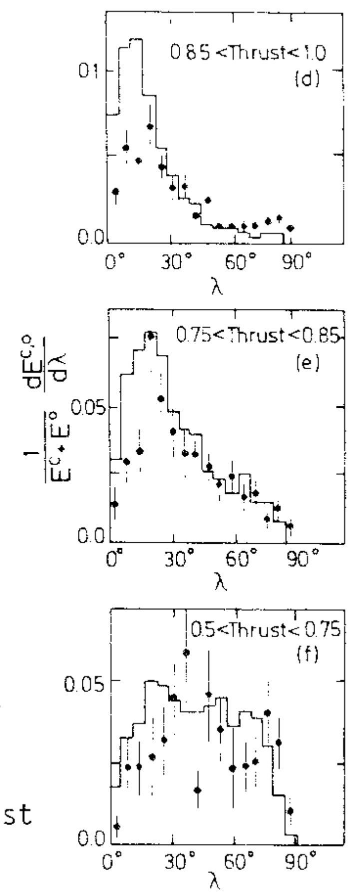


Fig. 13) Angular distribution of the charged energy (histograms) and the neutral energy (full points) with respect to the thrust axis at 9.4 GeV from PLUTO [42].

By requiring at least 4 tracks half of the $\tau^+\tau^-$ events are cut out . The mean observed sphericity falls with increasing energy, which implies that the events become more jetlike. A calculation of the jet model of Field and Feynman [44] at 9.4 GeV (cross in Fig. 11) is in agreement with the data, whereas a phase space model (hatched band in Fig. 11) does not reproduce the data, for $E_{CM} \gtrsim 5$ GeV. The same observations are made when the quantity 1 - <T> is plotted (Fig. 11 b).

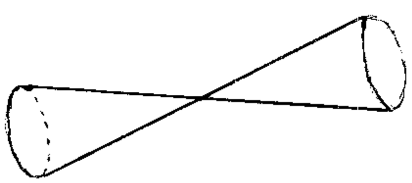
How well do the jet axes from the sphericity and thrust variables agree with each other ? Fig. 12 shows the distribution of the angle η between the two axes at 9.4 GeV. The distribution has a tail reaching up to 50^o. The average angle between the two axes is $\underline{15^o}$ at 9.4 GeV. This indicates the inherent uncertainty of the above jet axis determination due to the differences in the variables used and the neglect of the neutral energy.

3.5.2. How is the neutral energy distributed ?

The PLUTO detector has recently been upgraded by segmented shower counters (over 94 % of 4π). This allows a measurement of the neutral energy distribution. Fig. 13 shows the angular distribution $dE/d\lambda$ of the charged energy (histogram) and of the neutral energy (full points) with respect to the thrust axis for three intervals of T. We conclude from Fig. 13 that the neutral energy has approximately the same distribution in a jet as the charged energy *.

3.5.3. Average width of jets in space

From the angular distribution of neutral and charged energy the PLUTO group has determined the opening angle of a cone which contains 50 % of the charged and neutral energy[42]. They find a full opening angle of $\sim 54^o$ at 9.4 GeV. I.e. Jets at 9.4 GeV are still fairly wide. This agrees with the jet model of Ref. 44.



* The apparent excess of charged energy at small λ can be explained by the fact that the jet axis was determined from charged particles only.

3.5.4. Summary on jets

Fig. 14 shows a jet event from PLUTO, which demonstrates some of the characteristics discussed above.

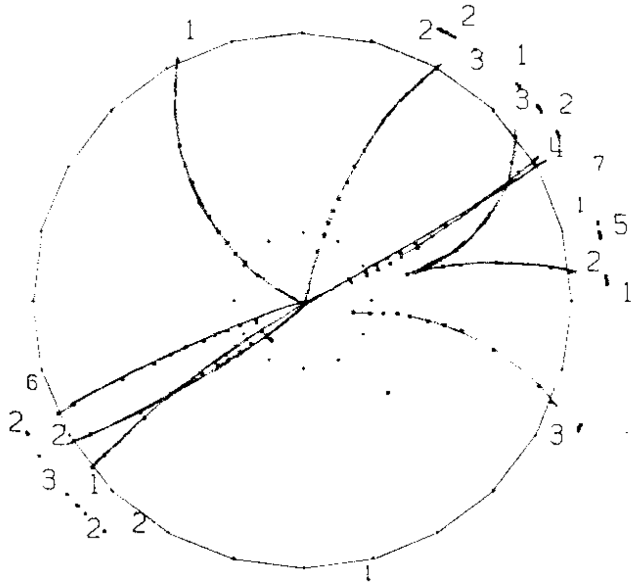


Fig. 14) A jet event from PLUTO taken at E_{CM} = 9.3 GeV (view along the beam). The numbers are shower counter pulse heights, measuring the neutral energy (plus part of the charged energy).

1) The neutral energy (indicated by the numbers in Fig. 14) follows the charged energy.
2) Jets at 9.4 GeV are still fairly wide. 50 % of the energy comes outside a cone of 54^o opening angle.
3) There is no unambiguous way to determine the jet axis from the data. The present uncertainty from using different jet axis definitions and charged particles only is $\sim 15^o$ at 9.4 GeV.
4) Still, we have very good evidence for the occurance of 2 jets in e^+e^- annihilation. The events become more jetlike with increasing energy.

4. Charmonium and charmed mesons

The spectroscopy of charmonium ($c\bar{c}$ - states) and charmed mesons ($c\bar{u}$, $c\bar{d}$, $c\bar{s}$ states) has been developing very fast in the years following the discovery of the J/ψ. However, not much new experimental information was added in the last year. Therefore I will cover only two topics, the photon cascade decays of the ψ' and the evidence for the F meson.

4.1. Cascade decays of the ψ'.

The assignment of the resonant states J/ψ and ψ' as the $1\,^3S_1$ and $2\,^3S_1$ states of charmonium leads to the prediction of further charmonium states with masses between those of J/ψ and ψ'. If such intermediate states have even C-parity, they can be reached via radiative transitions from ψ' and can also decay radiatively into J/ψ. Several such states have been observed in cascade decays of the type

$$\psi' \rightarrow \gamma\, P_c/\chi$$
$$\hookrightarrow \gamma\, J/\psi$$

as monochromatic lines in the inclusive photon spectrum and also in hadronic decays.

Fig. 15 a shows the scatter plot $M(J/\psi\ \gamma_L)$ vs. $M(J/\psi\ \gamma_H)$ from three experiments[45-47]. The labels L and H indicate the low and high mass solution of the $(J/\psi\ \gamma)$ - system. Three intermediate states are experimentally well established at masses of 3.41, 3.50 and 3.55. They appear as clusters in $M(J/\psi\ \gamma_H)$. The states are generally interpreted as being the $^3P_{0,1,2}$ states of charmonium, respectively. There is some evidence for a fourth state at 3.45 GeV, which is often associated with the $2\,^1S_0$ state (known as η_c').

The DESY-Heidelberg group has reanalyzed their cascade decay data, resulting in a smaller event sample with improved mass resolution[48]. This is shown in Fig.15b. The projection of the high mass solution shows clearly the two states at 3.5 and 3.55 GeV. There is also an excess of 5 events at 3.59 GeV above a zero expected background indicating the existence of an additional state. By choosing the low mass solution the mass of the state would be at 3.18 GeV. The data contain no evidence for the $\chi(3.45)$. Table 3 summarizes the branching ratios for the P_c/χ states reported so far. Clearly the field deserves further experimental study.

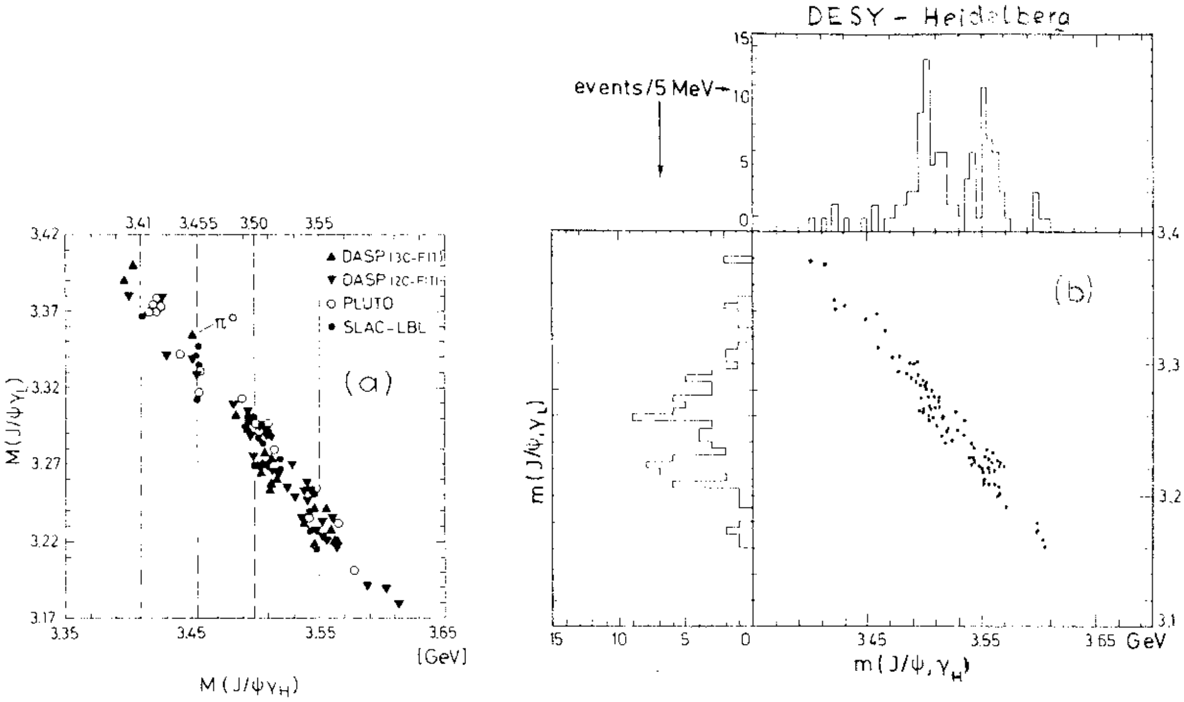


Fig. 15) Scatter Plot of the low mass vs. the high mass solution of the $(J/\psi\gamma)$ system in cascade decays $\psi' \to \gamma\gamma\ J/\psi$. a) Data from DASP [45], PLUTO [47] and SLAC- LBL [46]. Note that the statistics of the DASP data was increased since last year. b) Data from ref. 48.

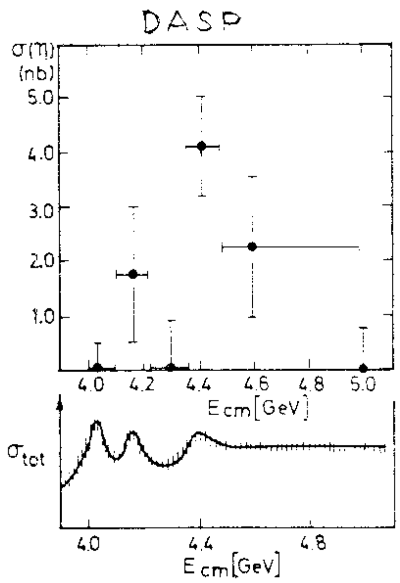


Fig. 16) Top: Inclusive η cross section from events containing at least 2 charged particles [35]. Bottom: Energy dependence of the total hadronic cross section.

Table 3: Branching ratio products B ($\psi' \to \gamma\chi$) • B ($\chi \to \gamma J/\psi$) in %.

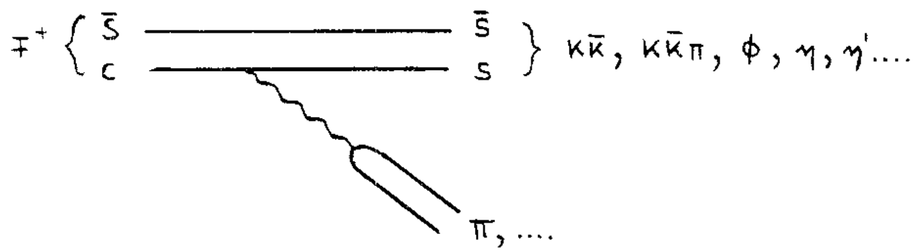
State	DASP [45]	DESY-HD [48]	MPPSSSO [49]	SLAC-LBL [46]	PLUTO [47]
$\chi(3415)$	0.3 ± 0.2	0.14 ± 0.09	3.3 ± 1.7	0.2 ± 0.2	$1.2^{+0.9}_{-0.6}$
$\chi(3454)$	<0.4(90%c.l.)	<0.25(90%c.l.)	<2.5(90%c.l.)	0.8 ± 0.4	$0.7^{+0.8}_{-0.5}$
$P_c/\chi(3510)$	1.7 ± 0.4	2.5 ± 0.4	5.0 ± 1.5	2.4 ± 0.8	$1.2^{+1.0}_{-0.6}$
$\chi(3550)$	1.4 ± 0.4	1.0 ± 0.2	2.2 ± 1.0	1.0 ± 0.6	$0.9^{+1.0}_{-0.5}$
$\chi(3590)$ or $\chi(3180)$		0.18 ± 0.06			

4.2. The F - mesons

The charm model predicts mesons carrying both charm and strangeness. The ground state is the F^+. Assuming that

$$M_F < M_D + M_K$$

the particle can only decay weakly into a $s\bar{s}$ system. This leads to final states containing $K\bar{K}$, ϕ, η or η'.



The DASP group reported first evidence for F production a year ago [6,50]. In the meantime they have extended their analysis [35]. The group studies F decays into η's. The η's are detected via the $\eta \to \gamma\gamma$ decays in events containing at least two charged tracks.

$$e^+e^- \to \eta + \geq 2 \text{ charged tracks} + X$$
$$\hookrightarrow \gamma\gamma$$

Fig. 16 shows the inclusive η production cross section derived from the data. For comparison, the trend of the total cross section is indicated in the lower part of the figure. Strong η signals are present at 4.16 and 4.41 GeV, whereas no η production is observed at 4.03 GeV. Since D and D^* production is strong at 4.03 GeV, this implies that the η production cannot be associated dominantly with D and D^* meson production or decay.

The DASP group were able to show that part of their η signal is correlated with electrons, which is indicative of the weak decay origin of these particles.

In analogy to the copious DD^* and D^*D^* formation near 4.03 GeV one expects large FF^* and F^*F^* cross sections near threshold. If both the F and F^* are isoscalars (I=0) and if

$$M_{F^*} < M_F + 2M_\pi ,$$

the dominant decay mode of the F^* should be

$$F^* \to F\gamma .$$

The signal for F production can therefore be enhanced by requiring a low energy photon in addition to the η signal. Such events are found at 4.4 GeV, but not at the other energies. Events which have a soft photon <u>and</u> an identified π meson, were fitted to the hypotheses (2 C Fit).

$$e^+e^- \to F^\pm F^{*\mp} \quad \text{(A)}$$
$$F^{*\mp} \to F^\mp \gamma_{low}, \quad F^\pm \to \pi^\pm \eta$$

$$e^+e^- \to F^{*+} F^{*-} \quad \text{(B)}$$
$$F^{*+} \to F^+ \gamma_{low}, \quad F^+ \to \pi^+ \eta$$

The fit yields a clear clustering of 6 events with very little background. From the fits to (A) and (B), the masses could be determined as $M_F = 2.03 \pm 0.06$ GeV and $M_{F^*} = 2.14 \pm 0.06$ GeV. The mass difference is $M_{F^*} - M_F = 0.110 \pm 0.046$ GeV and the relative branching ratio $B\,(F \to \eta\pi)\,/\,B\,(F \to \eta X) = 0.10 \pm 0.04$. These results increase the evidence for the F meson. Up to now they have been neither confirmed nor contradicted by any other experiment [3].

5. The Υ and Υ' mesons

5.1. The observation of the Υ meson in e^+e^- annihilation

In June 1977 the Columbia-FNAL-Stony Brook Collaboration announced the discovery of a resonant meson state at 9.4 GeV, which they called the Υ meson [51,52]. The Υ was observed in the $\mu^+\mu^-$ decay mode typical of a vector meson. In addition to the peak at 9.4 GeV the $\mu^+\mu^-$ mass distribution showed the presence of at least one higher mass state (see Fig. 17).

The surprising discovery of such high mass resonances immediately raised the question : Are the peaks a replay of the narrow ψ and ψ' states ? Is the Υ a bound state of a new type of quark ($\Upsilon = b\bar{b}$) ? It was obvious,that one needed a much better mass resolution to answer these questions.

In July 1977 the PLUTO group proposed to upgrade DORIS up to 10 GeV for a measurement of the Υ. DORIS provides an energy resolution of σ = 7.5 MeV at 9.4 GeV, in contrast to $\sigma_M \approx 200$ MeV of the FNAL experiment. The good energy resolution of e^+e^- storage rings is a crucial advantage in the search for narrow high mass vector mesons.

DORIS had to be converted to a single bunch machine. Energies of 9.2 GeV were reached in early April 1978. After a 20 days scan the Υ peak was hit on April 30. It was observed simultaneously in the PLUTO[53] and DASP[54*] detectors at 9.46 GeV. The resulting excitation curves are shown in Fig. 18 and Fig. 19a. Two months later, the Υ was also measured by the newly formed DESY-Hamburg-Heidelberg-München Collaboration[55] using the existing DESY-Heidelberg detector (Fig. 19b). The results in Fig. 19a are not absolutely normalized. All three experiments found that the width of the observed peak could be explained by the beam energy width of DORIS. Hence the full width of the Υ must be smaller than 18 MeV. This supported the identification of the Υ with a ψ like narrow state and lead to the questions :

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* The DASP detector is now being used by a new DESY-Dortmund-Heidelberg-Lund Collaboration (DASP2).

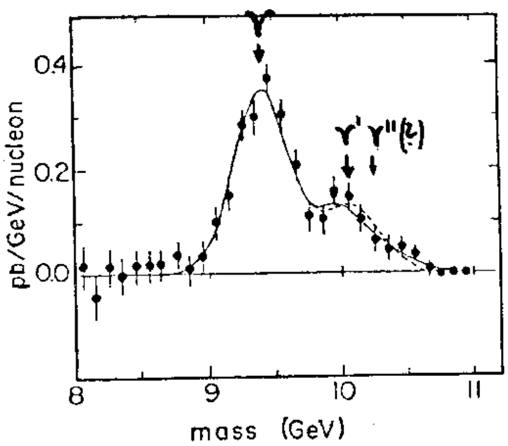

Fig. 17) $\mu^+\mu^-$ mass distribution (after non resonant background subtraction) from reaction p nucleus → $\mu^+\mu^-$ X at 400 GeV/c [52].

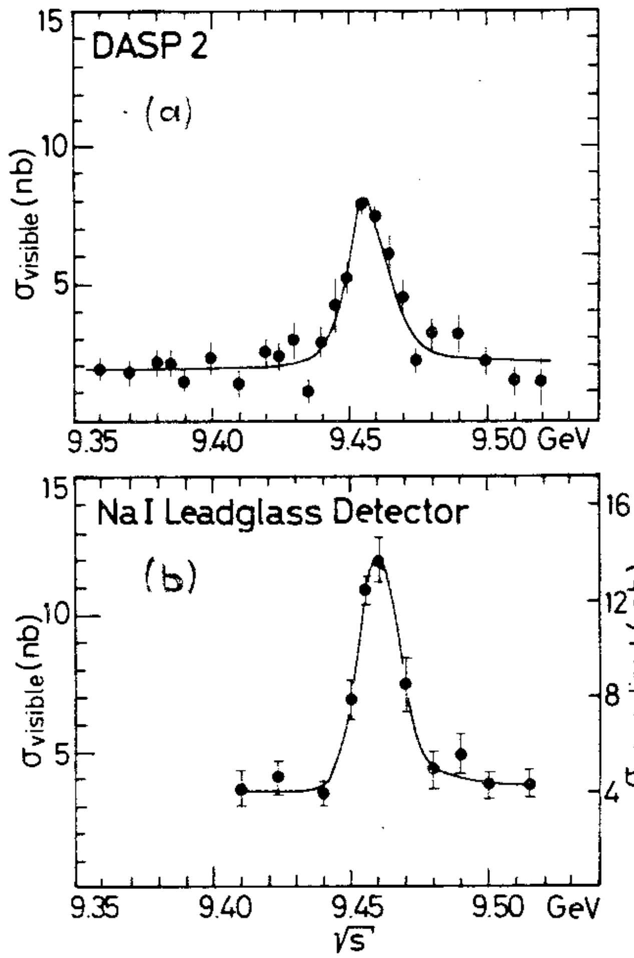

Fig. 19) Observed cross section near the Υ resonance from the DASP 2 [54] and the DESY-Hamburg-Heidelberg-München Collaboration [55].

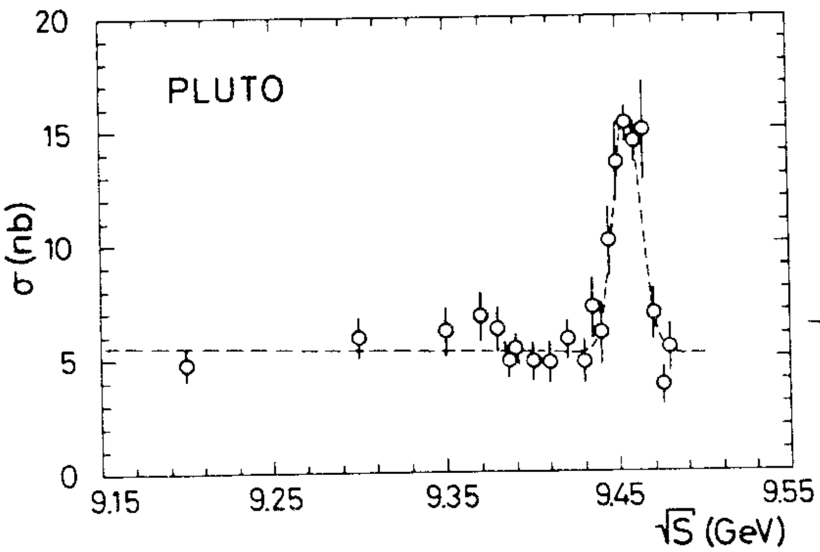

Fig. 18) Total hadronic cross section near 9.4 GeV from PLUTO [53]. The $\tau^+\tau^-$ events are still included. No radiative corrections have been applied.

1) What are the Υ parameters (Γ_{tot}, Γ_{ee}, etc.) ?
2) How many states are there ?
3) If the Υ is a bound state of new quarks, is the quark charge - 1/3 or 2/3 ?
4) Does the Υ decay show features of a 3 gluon decay as predicted by QCD ?

5.2 Υ - Parameters

The Υ parameters measured by the three DORIS experiments are listed in Table 4. The electronic width Γ_{ee} was obtained from the integral over the resonance cross section σ_{had} via

$$\frac{M_\Upsilon^2}{6\pi^2} \int \sigma_{had}\, dE = \frac{\Gamma_{ee}\,\Gamma_{had}}{\Gamma_{tot}} \approx \Gamma_{ee},$$

where one assumes $\Gamma_{tot} \approx \Gamma_{had} >> \Gamma_{ee}$.
(M_Υ = mass of Υ, Γ_{had} = hadronic decay width of the Υ, Γ_{tot} = total width)

Table 4: Υ parameters as measured at DORIS

	PLUTO [53,64]	DASP 2 [55,61]	DESY-HBG-HD-München [55]	average
M_Υ (GeV)	9.46 ± 0.01	9.46 ± 0.01	9.46 ± 0.01	9.46 ± 0.01 *
Γ_{ee} (keV)	1.3 ± 0.4	1.5 ± 0.4	1.04 ± 0.28	1.2 ± 0.2
$B_{\mu\mu}$ (%)	2.7 ± 2.0	2.5 ± 2.1	$1.0 \begin{smallmatrix} +3.4 \\ -1.0 \end{smallmatrix}$	2.6 ± 1.4
Γ_{tot} (keV)	> 20 (95% c.l.)	> 20 (95% c.l.)	> 15 (95% c.l.)	> 25 (95% c.l.)

* error due to beam calibration uncertainty

A measurement of the branching ratio $B(\Upsilon \to \mu\mu) = B_{\mu\mu}$ then allows one (in principle) to derive the total width (assuming μ - e universality) via

$$B_{\mu\mu} = B_{ee} = \frac{\Gamma_{ee}}{\Gamma_{tot}} \to \Gamma_{tot} = \frac{\Gamma_{ee}}{B_{\mu\mu}} .$$

In all three experiments the determination of $B_{\mu\mu}$ suffers from low statistics. For example the PLUTO group found 60 μ pairs off resonance and 74 μ pairs on resonance [64]. Even if all data are combined, the errors are still too large to obtain a two standard deviation upper limit on the total width. One can only obtain a (conservative) lower limit of 25 keV on a 95% confidence level.

5.3. How many higher mass states are there ?

An obvious consequence of the successful measurement of the Υ at DORIS was to search for the next higher state, the Υ'. In August 1978 DORIS reached a total energy of 10 GeV, which is very close to its maximum energy. In the last three days before the Tokyo conference both the DASP 2 and the DESY-Hamburg-Heidelberg-München Collaboration found a narrow peak at 10.015 GeV, which is to be identified with the Υ'. Fig. 20 shows the observed cross section near the resonance. The measured parameters of the Υ' are given in table 5.

Table 5: Υ' parameters as measured at DORIS

	DASP 2 [56]	DESY-HBG-HD-München [55]	Average
$M_{\Upsilon'}$ (GeV)	10.01 ± 0.02	10.02 ± 0.02	10.015 ± 0.02
$M_{\Upsilon'} - M_{\Upsilon}$ (MeV)	555 ± 11	560 ± 10	558 ± 10
Γ_{ee} (Υ') (keV)	0.35 ± 0.14	0.32 ± 0.13	0.33 ± 0.10

The mass difference between the Υ and Υ' is smaller than the mass difference of 591 MeV between the ψ and ψ'. When the Υ and Υ' mass values from DORIS are used as fixed input in a fit to the FNAL data, then the evidence for the existence of a Υ'' state at 10.38 GeV rises from 4 to 13 standard deviations [57]. Hence we now have good evidence for three states of the Υ family.

5.4. The charge of the constituent quarks

The charge of the constituent quarks of the Υ and Υ' can be inferred from the measured electronic widths. Rosner, Quigg and Thacker have analyzed a large class of quarkonium models [58]. They derived lower limits to $\Gamma(\Upsilon \to ee)$ and $\Gamma(\Upsilon' \to ee)$ for both charges 1/3 and 2/3, assuming conservative input values.

The hatched area in Fig. 21 shows the allowed region for charge 2/3, whereas the triangular region is the favoured region for charge 1/3. The measured point from DORIS falls right on the latter region. The point is 3σ away from the lower limit assuming charge 2/3. Hence the data clearly favour a charge assignment of 1/3 for the constituent quark of the Υ.

5.5. Jet structure on the Υ.

In the framework of QCD the Υ meson is expected to decay into three gluons, which subsequently fragment into hadrons. Hence the occurence of three jet events has been postulated by many theorists in the hope of finding experimental evidence of the gluons [43].

The three DORIS experiments have analyzed the jet structure on the Υ. Before I present the results I would like to indicate the theoretical and practical complications, which make the identification of a 3 jet structure difficult :

a) Jets from a three gluon decay of the Υ (9.46) are very likely wider than jets from regular 2 jet events at 9.4 GeV, since less energy per jet is available.
b) A specific QCD calculation of Koller, Walsh and Krasemann [59] predicts that the angular configuration of the three jets is not symmetrical (Mercedes star) but that the average angle between 2 of the 3 jets is only 57^{o} which causes a strong overlap between these two jets (see section 3.5.3)

Hence the unambiguous identification of three separate axes is a non-trivial problem. In addition, a background subtraction has to be performed. The cross section measured at the resonance peak has three contributions :

1) The non-resonant one photon exchange continuum yielding regular 2 jet events (Fig. 22a)
2) The vacuum polarization term, which again results in 2 regular jets (Fig. 22b). This term is proportional to $R \cdot B_{\mu\mu}$ and represents about 13 % of the on -resonance cross section.
3) The direct decay of the Υ. (Fig. 22c).

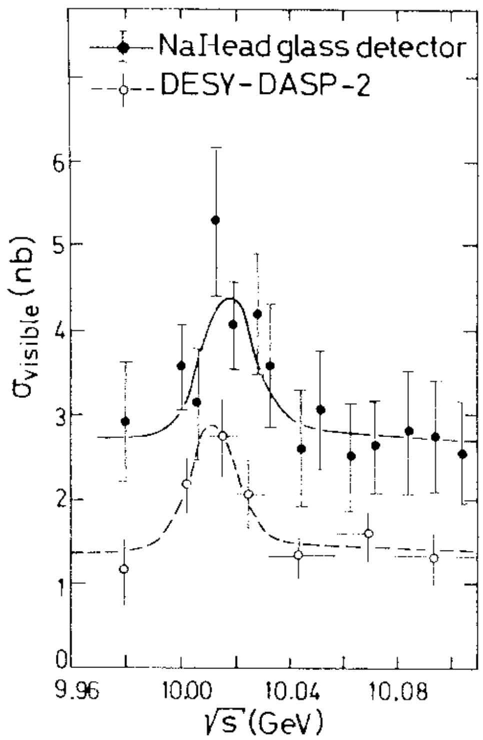

Fig. 20) Observed cross section near the Υ' resonance from the DASP 2 (open points)[56] and the DESY-Hamburg-Heidelberg-München Collaboration[55] (full points).

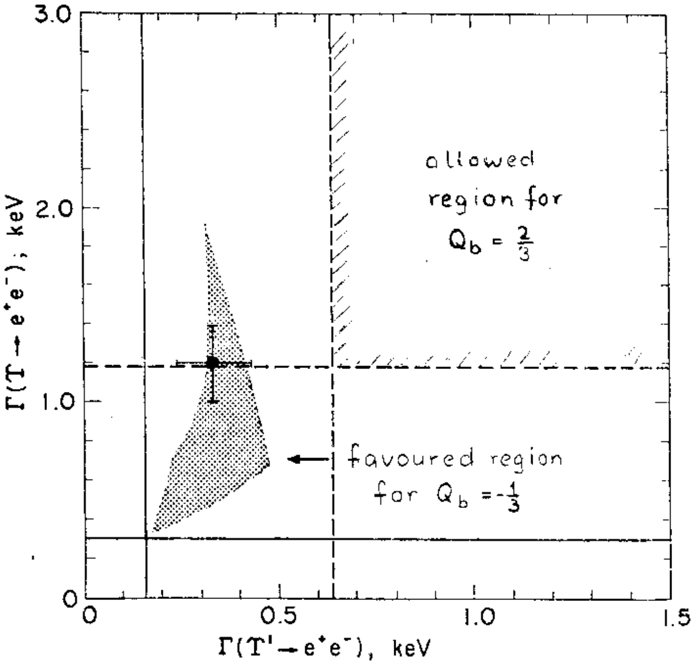

Fig. 21) Quarkonium model predictions of ref. 58 for $\Gamma(\Upsilon \to ee)$ vs. $\Gamma(\Upsilon' \to ee)$ and average measured value from DORIS (full point) as given in tables 4 and 5.

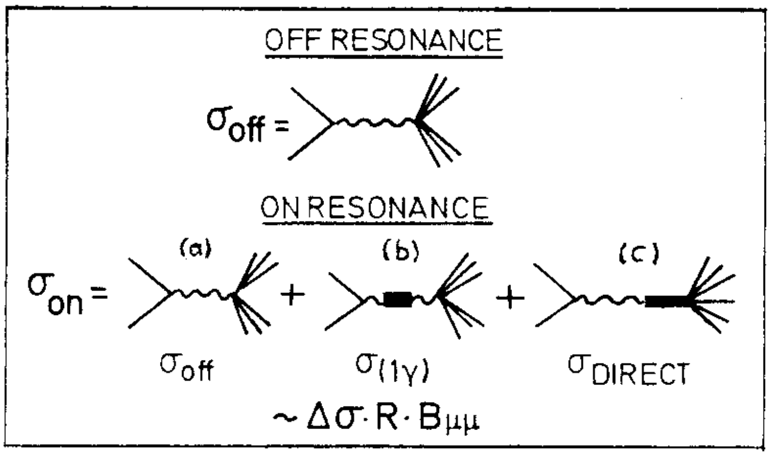

Fig. 22

Since we are here only interested in the direct Υ decay, the first two contributions have to be subtracted. The subtraction is performed on a statistical basis using events in the side bands of the Υ peak.

The analysis of the jet structure on the Υ made use of several approaches [55,60,61]. We report here on the sphericity and thrust analysis of the PLUTO data [3,60], which was already applied off resonance. Any widening of the event with respect to a regular 2 jet structure should lead to an increase of the mean sphericity. This is indeed observed, as shown in Fig. 23 a. The insert shows the variation with energy of the mean observed sphericity. After averaging over the peak and subtracting the non-direct background, the mean observed sphericity for direct Υ decay is obtained (open square in Fig. 23 a). It is as high as that from ψ resonance decays.

The measured value comes very close to the value of 0.4 predicted by Hagiwara [62], assuming a three gluon decay of the Υ. Note that the data point (Υ direct) is only 3σ away from the region of the phase space model. The same observations are made when $1 - \langle T \rangle$ is plotted (Fig. 23b). The $1 - \langle T \rangle$ value from direct Υ decays is to be compared to the QCD prediction of 0.25 from Ref. 59. Hence the data are consistent with QCD calculations. However the existence of three separate jets could not be established so

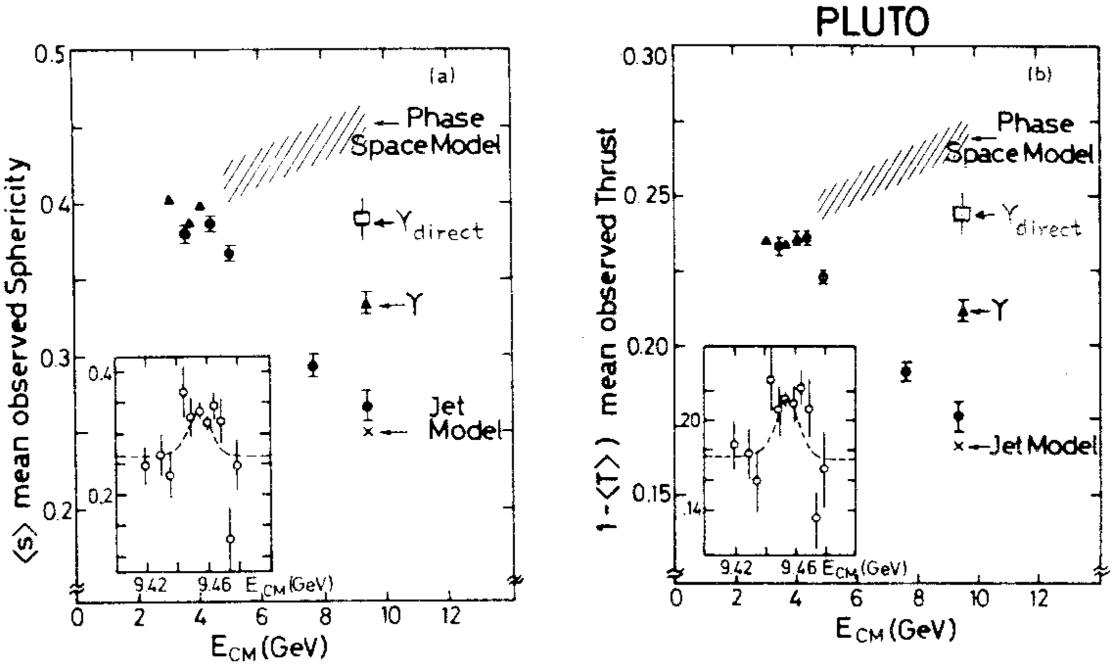

Fig. 23a) Mean observed sphericity from charged tracks as a function of E_{CM} from the PLUTO detector [3, 60]. Meaning of symbols: $\blacktriangle$ = <s> measured on the Υ peak, ⊡ = <s> from direct Υ decays. b) Same as a) but showing $1-\langle T\rangle$. The insets show the data in the Upsilon region together with a Gaussian curve with the mass and width from a fit to the total cross section.

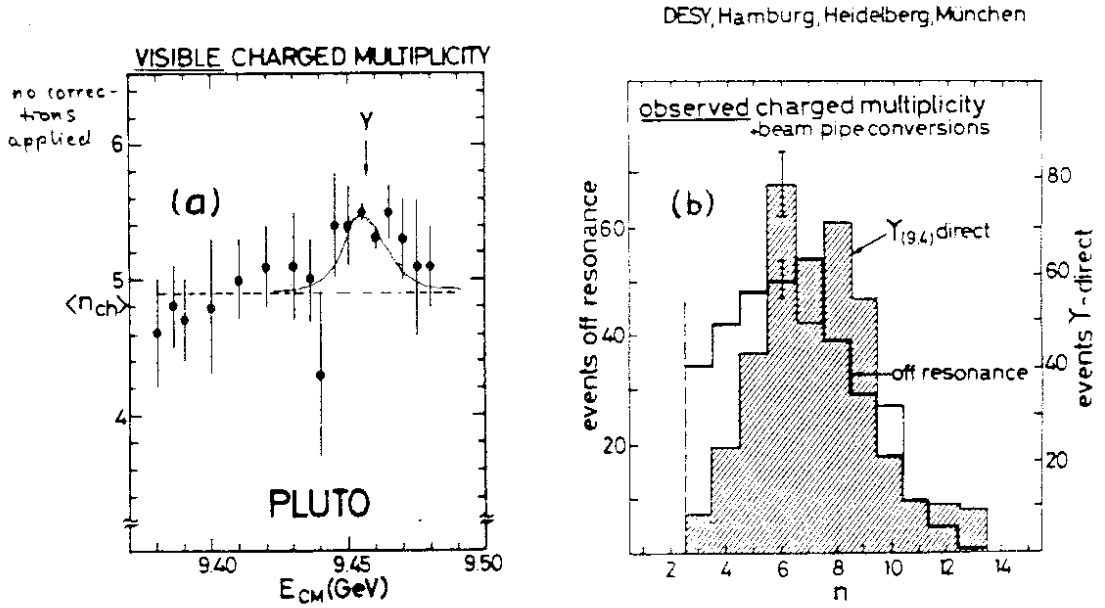

Fig. 24a) Visible charged multiplicity vs. E_{CM} from the PLUTO detector [64]. b) Charged multiplicity distribution on and off the Υ from ref. 55. The on resonance data in b) (not in a) were obtained after a subtraction of the continuum and vacuum polarization contribution.

far. The proximity of the data to a phase space pattern makes further conclusions difficult *.
It has been speculated that the mean multiplicity of a resonance decaying into three gluons should increase considerably from the off resonance value [63]. Fig. 24a shows the visible mean charged multiplicity as a function of E_{CM} from the PLUTO detector [64]. A significant increase is observed on the Υ peak. Similarly the prong number distribution of charged tracks (including tracks from photon conversions in the beam pipe) from ref. 55 is shifted to higher values on the Υ (see fig. 24b). An increase of multiplicity was also seen in the DASP 2 experiment [61]. The results are summarized in table 6.

Table 6 : Observed particle multiplicities near the Υ.

	PLUTO	DESY-Hbg. Hd-München	DASP 2
$\langle n_{ch} \rangle$ off reson.	5.0±0.1	6.4±0.2	5.2±0.1
$\langle n_{ch} \rangle$ on reson.	5.4±0.1	6.9±0.2	5.7±0.1
$\langle n_{ch} \rangle$ Υ direct	5.9±0.1	7.3±0.2	6.2±0.1

The numerical values from the three experiments differ since each experiment has different acceptance criteria and no corrections have yet been applied.**
The important conclusion is that all experiments find an increase of one unit in $\langle n_{ch} \rangle$. This again is consistent with QCD ideas but does not bear conclusive evidence.

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* Note also that the experimental sphericity and thrust values are not yet corrected for track losses and radiative effects. Acceptance corrections are however expected to be not very large.

** In particular tracks from photon conversions have not been subtracted in these experiments.

6. Conclusions

Let me summarize what we have learned from the above data:

1) The τ is now firmly established as a new heavy lepton with standard V-A interactions.

2) General properties of hadron production like σ_{tot} and 2 jet structure are qualitatively well described by the quark-parton model. Jets at 9.4 GeV are still fairly wide.

3) The experimental situation of the η_c' has not been cleared up. There is some indication for a χ state at 3.59 (or 3.18) GeV.

4) The Υ and Υ' mesons have been found in e^+e^- annihilation at 9.46 and 10.015 GeV. The constituent quarks have very likely charge 1/3 (not 2/3). Using the Υ and Υ' mass values from DORIS as an input there is firm evidence from the FNAL data for a Υ'' at 10.38 GeV.

5) The event structure changes considerably from 2 jet at 9.4 GeV to an almost isotropic structure on the Υ in accordance with QCD calculations. But the identification of three separate jets has not been possible so far and will be difficult in the future.

6) We have growing evidence that a fifth type of quarks (b quarks) forms the constituents of the Υ and Υ' mesons. This opens a rich field of exploration for the next round of e^+e^- experiments, both in $b\bar{b}$ and B particle spectroscopy as in the search for states containing a sixth quark expected on the basis of lepton-quark symmetry.

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