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Particle Spectroscopy

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I. INTRODUCTION

During the last years particle spectroscopy has evolved into a spectroscopy of leptons and quarks. This era was initiated in 1974 by the discovery of the J/ψ mesons$^{1)}$, quickly followed by the new lepton τ $^{2)}$ and finally by the Ypsilon meson$^{3)}$. One is therefore tempted to outline this talk following the common prejudice that high energy physics can be described by leptons, quarks and their mutual interactions (Fig. 1).

Let me first say a few words about the subjects I am not going to cover. I will not talk about leptons. You just heard a beautiful review of the new lepton τ by Gary Feldman in the previous talk$^{4)}$. I will be brief also on the old quarks u, d and s since the old hadron spectroscopy will be covered in the next talk by R. Cashmore$^{5)}$. In my talk I will just concentrate on one specific aspect of old hadrons, namely exotics. The main part of my report will then be devoted to the new quarks charm and beauty. Being inspired by Sosnowsky's talk$^{6)}$, I will also try to offer you a jet tour, starting with 2 jets in e^+e^- reactions and leading eventually to a glimps on three gluon jets at the Ypsilon.

II. EXOTICS

The possible existence of exotic particles has mainly been discussed in the context of two hypothetical quark compounds, dibaryons$^{7)}$ and baryonium$^{8)}$. Dibaryons are constructed from the old baryons by doubling the quark content of the particle from 3 to 6 quarks. Similarly baryonium evolves from the concept of mesons $q\bar{q}$ by doubling the quark content giving $qq\bar{q}\bar{q}$ states.

II.1 Baryonium - Broad States

Experimentally baryonium is readily defined as mesonic states with strong coupling to an antibaryon-baryon ($\bar{B}B$) system . First observations of this kind of phenomenon were made in the famous S, T and U states, which reveal themselves as resonance in the elastic, total and annihilation cross sections of nucleon-antinucleon ($N\bar{N}$) systems with a large elasticity$^{8,9)}$.

Table 1 summarizes the situation encountered in 1977. The S, T and U states were seen in many experiments on $N\bar{N}$ cross sections. In particular an analysis of the reaction $p\bar{p} \to \pi^+\pi^-$ by Carter et al. gave clear evidence for the existence of $J^{PC} = 3^{--}$ $(I = 1)$, $J^{PC} = 4^{++}$ $(I = 0)$, and $J^{PC} = 5^{--}$ $(I = 1)$ states[9]. In 1978 Carter et al. extended their analysis to the reaction $\bar{p}p \to K^+K^-$ and established the presence of $I = 0$ components with $J^{PC} = 3^{--}$ and 5^{--} as well[10]. Dulude et al. analysed the reaction $\bar{p}p \to \pi^0\pi^0$ and found a state with $J^{PC} = 2^{++}$ $(I = 0)$ at 2.1 GeV[11]. Further data became available from a measurement of $\pi^- p \to \bar{p}pn$ by the Bari-Bonn-CERN-Daresbury-Glasgow-Liverpool-Milano-Vienna-collaboration at the Omega spectrometer at CERN[12]. They found evidence for at least three broad resonances at 1950, 2100 and 2300 MeV with $J^P = 1^-$, 3^- and 4^+, respectively and may be an additional 2^+ state at 2000 MeV[12].

In summary there is good and increasing evidence for the existence of broad $\bar{N}N$ states and in the S, T and U range. However, the situation seems to be rather complex since $I = 0$ and 1 Regge recurrences with $J = 3$, 4 and 5, and may be also $J = 1$ and 2 are encountered. The best established state is certainly the S resonance[13] (new evidence became available from a Tokyo-Massachusetts collaboration at this conference[14]). However, there is no J^P determination of this state so far, and it may even have two J^P components[15].

II.2 Baryonium - Narrow States

We have good evidence for the existence of broad states coupled to the $\bar{B}B$ system. Of course, it is by no means clear that this has something to do with exotics. A possible description of these states would for instance be to view them as $\bar{B}B$ bound states. The narrow width of the S state could be explained due to its vicinity to the $\bar{B}B$ threshold. However, in 1977 narrow high mass states coupled to $\bar{B}B$ were discovered. There seemed to be no possible explanation for these states in the usual framework of meson spectroscopy. They could indeed be viewed as good candidates for baryonium states.

The existence of such $qq\bar{q}\bar{q}$ compounds was first predicted by Rosner from duality arguments[16]. For such meson states a strong coupling to $\bar{B}B$ and the apparent reluctance to decay into usual mesons can be explained by an OZI rule analogon[17] (Fig. 2).

The elaboration of these ideas does explain both narrow and broad states in the $\bar{B}B$ system at least qualitatively[18]. The three best candidates for narrow $\bar{B}B$ states are compiled in Table 2 together with the S state.

The first one, a narrow state at 2.95 GeV with a width of less than 15 MeV, was first seen in 1977 at the CERN-Omega spectrometer by the Bari-Bonn-CERN-Daresbury-Glasgow-Liverpool-Milano-Purdue-Vienna-Collaboration in the reaction $\pi^- p \rightarrow p\bar{p}\,\pi^-$ + anything. It showed up as a spike in the $\bar{p}p\pi^-$ mass distribution[19]. Since then this experiment has been repeated with 10 times more statistics. As we heard on this conference there are no definite new results yet. An analysis of part of the data did not confirm the effect[20]. Consequently, the existence of this resonance seems to be questionable.

The other two candidates were seen in the reaction $\pi^- p \rightarrow \pi^- pp\bar{p}$. Imposing the condition that the forward proton and the π^- form an N^* or a Δ, the remaining $\bar{p}p$ system exhibits two spikes at 2.02 and 2.2 GeV (Fig. 3). They can be viewed as resonances in the off shell $\bar{p}p$ scattering of the baryon exchange reaction. The experiment was repeated by the Toronto-York-Purdue-Collaboration with positive pions[22]. They find some indication for a 2.2 GeV state with a statistical significance of 2 standard deviations. The experiment does not confirm the 2.95 state. The Pittsburgh-Massachusetts-Collaboration has looked into the reaction $\bar{p}p \rightarrow \pi^+_f \pi^- K^+ K^-$[23]. They see an indication for the existence of the 2.2 GeV state in the $\pi^- K^+ K^-$ system with a statistical significance of 4 to 5 standard deviations. If this were confirmed it would mean that the 2.2 state is an isovector state. As we have heard in P. Söding's talk there is also evidence for the 2.02 state beeing seen in the virtual photon production reaction $\gamma_V\, p \rightarrow \bar{p}\, pp$ at Cornell[24]. The statistical significance of this effect is 3 standard deviations. To summarize: There seems to be evidence confirming the existence of two narrow states at 2.02 and 2.20 GeV from several other experiments.

II.3 Dibaryons

Let us see whether even higher combinations do exist, for example a 6 quark combination like the dibaryon states mentioned above.

We all know at least one candidate for dibaryons, the deuteron. We know also that this is a nuclear force bound state and not the type of exotics we are looking for. Real exotic dibaryon states were for instance predicted in the MIT bag model by Jaffe in 1977[25]. I will only summarize the three best candidates and refer for all details to the parallel session.

The first candidate is a pp resonance at 2.26 GeV first seen in the Argonne total cross section experiment with polarized targets and beams[26]. The resonance known as the $^3F_3$ has a width of 200 MeV and the quantum numbers $J^P = 3^-$ ($I = 1$)*. The possible existence of further pp states was discussed at this conference27).

The second candidate comes from the Tokyo-KEK measurements on the photodesintegration of deuterons28). The analysis of these data reveals the possible existence of a $\Delta\Delta$-resonance at a mass of 2.38 GeV with a width of 200 MeV, and $J^P = 3^+$ ($I = 0$). $J^P = 1^+$ cannot be ruled out.

The third candidate, a strange dibaryon state, has been seen in many experiments29,30). A recent analysis was carried out by the CERN-Heidelberg-München-Collaboration30). In the reaction $K^-d \rightarrow \Lambda p\pi^-$ they find a narrow bound state in the Λp system with a mass of 2.129 GeV, a width of less than 10 MeV, and $S = -1$.

II.4 Exotic Quantum Numbers

Although there are several candidates for baryonium and dibaryon states, the only convincing argument in favour of exotic states would be the discovery of states with exotic quantum numbers.

Two searches for such states have been reported at this conference. The first one by the Indiana-Purdue-SLAC-Vanderbild-Collaboration, does not show any evidence31). The second one, however, from the CERN-Omega spectrometer by the Glasgow-DESY-Collaboration, does indeed show an effect in the reaction $K^+p \rightarrow \bar{\Lambda}p\pi^+n$32). Applying a fit to this reaction and constraining the $\bar{\Lambda}p\pi^+$ system to either $\bar{\Lambda}\Delta^{++}$ or $\bar{\Sigma}p$ they see a spike in the mass distribution of the $\bar{\Lambda}p\pi^+$ system (Fig. 4). It has a statistical significance of 3 to 5 standard deviations and certainly needs experimental confirmation.

II.5 Summary

To conclude this part there is no firm evidence for exotic quantum numbers so far. There have been many sightings of baryonium, narrow and wide, and dibaryon candidates. Qualitative arguments favour the exotic nature of the baryonium states. However, the high mass narrow states still need experimental confirmation. Convincing evidence for the exotic nature of these states is certainly yet missing. Consequently both experiments and theory have to be improved.

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[*] Details were also given in V.A. Tsarev's talk at this conference.

III. NEW QUARK SPECTROSCOPY

The rest of my talk will be devoted to the discussion of the two new flavours of quarks, charm and beauty. Since new results on the D meson were already discussed in the previous talk by G. Feldman[4)] I will concentrate on charmonium and the F meson in the context of charm. Concerning beauty I will show the experimental evidence for Ypsilon and Ypsilon Prime in e^+e^- reactions; I shall also talk about the event topology in the Ypsilon region discussing evidence for a 2 jet structure outside the resonance and the search for 3 gluon jets.

III.A Quark Charge

Before I go into a detailed discussion of the two new quarks let me briefly ask whether there is any experimental evidence supporting our common belief that quarks are fractionally charged. Two quantities might be used as a test for the quark charge.

The first one is the radiative width $\Gamma(\eta' \rightarrow \gamma\gamma)$. Since the η' is dominated by the SU(3) singlet amplitude there is a strong dependence of this quantity on the charge of the quarks. For fractional charge quarks (Gell-Mann quarks) a width of $\Gamma = 6.0$ keV is calculated whereas for integer charge quarks (Han-Nambu quarks) the width is $\Gamma = 25.6$ keV[33)]. Experimental results on this quantity have become available now from the Bonanza group at DESY[34)]. They looked for the two photon process $e^+e^- \rightarrow e^+e^-$ + hadrons with the two electrons tagged in the forward direction. The reaction was monitored by the two photon QED reaction $e^+e^- \rightarrow e^+e^-e^+e^-$ which was found to be in good agreement with predictions. From the fact that no final states of the type e^+e^- + hadrons were found they could infer an upper limit $\Gamma(\eta' \rightarrow \gamma\gamma) < 11.5$ keV (95 % confidence level). Previous results had been obtained by ADONE ($\Gamma < 33$ keV) and Imperial College ($\Gamma_{tot} < .8$ MeV) groups[35)].

The other test quantity is the width $\Gamma(J/\psi \rightarrow 3\gamma)$. Again the coupling depends on the quark charge and the predictions are 2.6 eV for fractional charge quarks and 13 eV for integer charge quarks[36)]. DASP has measured an upper limit on this J/ψ decay width giving $\Gamma < 5.1$ eV (95 % confidence level[37)]. Thus an integer charge of the quarks is ruled out by both experiments.
Of course, only a definite measurement of the widths could eventually support the fractional charge model.

III.B Charm

III.B.1 Charmonium

The $c\bar{c}$ system exhibits a series of bound states known as charmonium. The situation we faced one year ago is summarized in Fig. 5 38). We have a rather firm knowledge of the existence and even the spin assignment of the ^3P states. The situation is much worse on the ^1S states. Although the X(2820) was firmly established by the DASP collaboration37) and the existence of this state was confirmed in the reaction $\pi p \to \gamma\gamma n$ by the IHEP-CERN-Karlsruhe-Pisa-Vienna-Collaboration39), nothing - except its even C parity - is known about its quantum numbers. In particular its identity as η_c is certainly still questionable. The situation is even worse for the other state, the $\chi(3455)$ which was only seen in the $\gamma\gamma$ cascade decay of ψ'. It is statistically significant only when the results from three different experiments are combined. This situation has not changed since about 1.1/2 years except for some new results of the DESY-Heidelberg-Collaboration which I am going to describe now.

Fig. 6 shows the results of this group on the reaction $\psi' \to \gamma\gamma\, \underset{\hookrightarrow \mu\mu}{\psi}$ with the directions measured for both photons and the muons. Constraining the two charged particles to the J/ψ mass they obtain the mass distribution displayed in Fig. 6 for the high mass solution of the J/ψ γ-system. The two χ states at 3.5 and 3.55 GeV are clearly visible. Let me draw your attention to the excess of events above 3.55 GeV. It can not be explained by the $\pi^0\pi^0$ background (indicated by the dashed line) nor by tails of the 3.55 peak. This situation was known at the Hamburg conference one year ago40). Since then the DESY-Heidelberg group improved their mass resolution by taking only those events where the photons were converted in the inner detector41). This allowed a more precise determination of the angle of photon emission. Thus, with increased mass resolution but of course less statistics the group got the result displayed in Fig. 7a which indicates a clearly separated excess of events at 3.6 GeV. From these 5 events (above no background) the group concludes the possible existence of a state at 3.59 GeV with a branching ratio product

$$BR(\psi' \to \chi(3.6)\gamma) \cdot BR(\chi \to \gamma J/\psi) = (1.8 \pm 0.6) \cdot 10^{-3}.$$

The scatter plot (Fig. 7) of the low mass against the high mass solution of their data shows however, that the high mass solution is not unique. A low mass state at 3.18 GeV could be equally possible. Table 3 summarizes the situation on the branching ratios of the P_c/χ states in the charmonium system. Note that the new limit from the DESY-Heidelberg group for the $\chi(3.45)$ state is about a factor of 3 lower than the average value of about 0.7 % known so far. This casts new suspicion on the existence of this state.

To summarize, the situation on the charmonium ^1S states has not been cleared up during the last year. New data from the DESY-Heidelberg group rather question the state at 3.45 GeV, and point instead on the possible existence of another state at 3.6 GeV. Certainly more data is needed to clarify the situation.

III.B.2 Charm Particles

You all know the exciting story of the discovery of the D meson at SLAC[38,45) and you just heard a review of the situation by G. Feldman in the previous talk. Let me therefore only add some information on the particle which was still missing in the multiplet of pseudoscalar mesons of SU(4) shown in Fig. 8. Evidence for the existence of this pseudoscalar meson F and its vector counterpart F^* came from the DASP detector at DESY46). I am going to describe their new data in some detail47).

III.B.3 F Meson

If we assume that the mass of the F meson is smaller than the sum of the masses of the D and the K meson, the particle can only decay weakly with an $s\bar{s}$ system in the final state. Consequently we expect $K\bar{K}$, ϕ , η or η' in the debris of this decay. Since K's are difficult to spot in the heavy background of other charm particle production the DASP group looked for the inclusive production of η's in the reaction

$$e^+e^- \rightarrow \underset{\hookrightarrow \gamma\gamma}{\eta} + X$$

The experimental problem is of course the high combinatorial background of photons from multiple π^0's produced per event at these energies. The DASP group could, however, overcome this problem with a relatively good detection efficiency for photons (95 % above an energy of 140 MeV) and an angular and energy resolution which combine to give a mass resolution of about 80 MeV at the η. They select events with two charged particles and at least 2 photons with an energy of more than 140 MeV, an opening angle of more than 11.5^0 and a momentum vector sum of more than 300 MeV. With these cuts the π^0 efficiency is relatively low.

Fig. 9 shows the result of these measurements for 6 different energy intervals. The full curves are fits to the π^0 and η mass peaks on a background obtained by combining γ's from different events. The dashed curves indicate the background below the η signal.

Note that there is no η signal at 4.03 GeV whereas there is a clear signal at 4.16 GeV, a very strong signal at 4.42 GeV and maybe an indication of η production in the other energy regions. Fig. 9b summarizes the data in terms of the inclusive cross section for η production over the whole energy range from 4 to 5 GeV. For comparison the trend of the total cross section is indicated below the figure. The figure shows the inset of η production above about 4.1 GeV. Strong signals are present at 4.16 and 4.42 GeV. At both energies a resonance-like structure is visible in the total cross section. As mentioned by G. Feldman in the previous talk4) the detailed structure of the 4.16 GeV region is however controversial comparing SLAC4,48) and DESY49,5o) data.

Let me draw your attention again to the fact that no η production is present at 4.03 GeV. This is a crucial point in the whole argument since the spike at 4.03 GeV is known for abundant D production45). Consequently the lack of an η signal at this point indicates that the η production can not be explained by any known source including D production and decay.

The next point to check is whether the η's really originate from a weakly decaying particle. To check this all events were scanned for the presence of electrons. Fig. 10 shows e.g. the result for the 4.4 GeV region, where the η signal was strongest. Electron events are plotted against the $\gamma\gamma$ mass. The background due to misidentified electrons is indicated by a full line. The figure shows a strong signal above background in the region of the π^0 and the η mass. This indicates in particular that η production is correlated with the emission of electrons indicating the presence of a weak decay. If we assume now that the η production at 4.16 and 4.42GeV is due to F production one might suspect that at 4.42GeV at least F^* production is also involved. For the further argument let us therefore consider possible signatures for an F^*. Assume F and F^* are both $c\bar{s}$, $\bar{s}c$ states with different spin orientations. In this case both F and F^* are (I=0) states and the F^* can only decay into the F emitting an (I = 0) system. We further assume that the mass difference in the F F^* system is about equal to the mass difference in the DD^* system namely less than two times the pion mass. The only possible decay mode for the F^* will then be the decay

$$F^* \rightarrow F\gamma .$$

These considerations led the DASP group to look for the associated production of η with a soft photon possibly originating from the decay of F^* into F_γ. Fig. 11 shows the result of this search displaying again the mass of the $\gamma\gamma$ system at 3 different energy intervals. It shows again a strong η signal at 4.42GeV. No such signal is present above and below this energy range. This proves that at 4.42GeV η production is strongly correlated with low energy photons. One is therefore urged to look for direct evidence for FF^* or F^*F^* production at 4.42GeV. One assumes again that the F^* is cascading down to the F by emitting a soft photon and that one of the F particles decays into η and π. Therefore the DASP group looked into the reaction

$$e^+e^- \rightarrow \eta + \pi + \text{a soft photon} + X.$$

43 events of this type were found. The events were fitted to the hypothesis of F^*F^* or FF^* production. Fig. 12 shows the result for the case of FF^* production. The mass of the $\eta\pi$ system is plotted against the recoil mass. A clustering of 6 events can be seen at an $\eta\pi$ mass value of 2.03 ± .06 GeV. The background is less than 0.5 events.

Since the $\eta\pi$ system cannot unambiguously be associated to the F or the F^* and since also no clear distinction can be made between the FF^* and the F^*F^* hypothesis the recoil mass is not very suitable to determine the mass of the F^*. One can however infer the mass difference between F^* and F from the energy distribution of soft photons. The result is

$$M_{F^*} - M_F = 110 \pm 46 \text{ MeV}.$$

Taking into account all efficiencies the DASP group determined a relative branching ratio

$$BR(F \rightarrow \eta\pi) \,/\, BR(F \rightarrow \eta X) = 0.09 \pm 0.04.$$

The SLAC-LBL group also looked for a possible F production in the reaction

$$e^+e^- \rightarrow K^+K^-\pi + X,\ K^\pm K^0_S + X,\ K^+K^-\pi^+\pi^-\pi^\pm + X.$$

Constraining these data to the hypothesis that they originated from the process $e^+e^- \to F\bar{F}$ with a subsequent decay of one of the F to one of the above $(KK n\pi)$ systems they got a signal of about 4 standard deviations at a mass of 2039.5 ± 1.0 MeV$^{51)}$ at 4.16 GeV CM energy. The signal was not present in the equal sign KK systems. However, a repetition of the search in the MARKII detector could not confirm this result although it collected about the same statistics$^{52)}$.

D. Hitlin reported at this conference that the MARK II detector did not see any η signal at 4.16 GeV$^{53)}$. However, both MARK II and the DASP group agreed that due to the different experimental cuts this does not contradict the DASP result$^{53,54)}$.

To summarize, η production has been observed by the DASP collaboration above E_{CM}= 4.1 GeV. No η signal is seen at E_{cm} = 4.03 GeV. Strong η signals are present at 4.16 and 4.42 GeV, the latter being associated with soft photon production. The observed η production is correlated with electrons which is indicative for the weak decay origin of these particles.

From a study of $\eta\pi$ events with soft photons the masses of F and F^* could be determined as M_F = 2.03 ± 0.06 GeV, M_{F^*} = 2.14 ± 0.06 GeV. The relative branching ratio $BR(F \to \eta\pi) / BR(F \to \eta X)$ is 0.09 ± 0.04. These results are neither confirmed nor contradicted by any other experiment.

III.B.4 Summary

Our experimental knowledge on charm is schematically summarized in Fig. 13. The odd C-parity ^3S state J/ψ, its radial excitations ψ' and the ^3D state $\psi''(3.77)$ show up in the total e^+e^- cross section, the latter due to its mixing with the nearby ^3S state. The existence of the $\psi'(4.16)$ is somewhat controversial.

The ^3P states are established, although their quantum number assignment is not rigorously proven.
Whereas there is firm evidence for the X(2.82), the existence of the states $\chi(3.45)$ and $\chi(3.59)$ is not established. The quantum numbers of all three states are unknown, except for their even C-parity.

The upper part of Fig. 13 indicates, how the production of D, D^*, F and F^* mesons comes in with increasing energy: $D\bar{D}$ at the $\psi''(3.77)$, $D^*\bar{D}$ and $D^*\bar{D}^*$ at $\psi'(4.03)$, FF at $\psi'(4.15)$ and $F^*\bar{F}$ and/or $F^*\bar{F}^*$ at $\psi'(4.42)$. The evidence for

$F\bar{F}$ production at the ψ' (4.16) is suggestive but not compelling, since it is only based on the inclusive η signal of the DASP group. No clear distinction between $F^{*}\bar{F}^{+}$ and $F^{*}\bar{F}$ production at the ψ' (4.42) can be made.

III.C Beauty

Since the discovery of the Ypsilon meson by the Columbia-Fermilab-Stony Brook collaboration at FNAL in 1977 55) the new particle has been produced in various hadron experiments56) and the discoverers themselves improved both the statistics and the resolution of their experiment57). As L. Lederman outlined in his talk there is firm evidence for the existence of at least two Y states and some indications of even a third one56). The challenge for e^+e^- physics was of course to search for these new states as narrow resonances in e^+e^- collisions and thereby reveal their potential nature as bound states of new quarks. Therefore after the announcement of the discovery in June 1977 the PLUTO collaboration proposed in July 1977 to upgrade DORIS to reach the 10 GeV region. On April 12, 1978, the preparations were finished to start the search. Already on May 2, 1978, thanks also to the precise determination of the mass by the Columbia-Fermilab-Stony Brook collaboration, the Y was found at DORIS by the PLUTO58) and DASP2 59) collaborations simultaneously. The original data of this search are shown in Fig. 14 which displays the visible cross section in both detectors as a function of energy. A clear signal at 9.46 GeV is seen in both experiments.

From these original data both groups agreed on a mass value of $M_Y = 9.46 \pm .01$ GeV, an electronic width of $\Gamma_{ee} = 1.3 \pm .4$ keV and a total width of the resonance $\Gamma_{tot} < 18$ MeV. Note that the error on the mass is due to the DORIS calibration uncertainty and the width corresponds to the DORIS energy spread. These values already strongly favoured an interpretation of the Y being a bound state of a new quark antiquark pair with a charge of 1/3 58).

III.C.1 Ypsilon Parameters

The immediate issue of e^+e^- physics of the Y is of course a determination of the leptonic and the total width of the resonance. The leptonic width Γ_{ee} can be inferred directly by integrating the hadronic cross section of the resonance according to the formula

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

assuming $\Gamma_{ee}/\Gamma_{had} << 1$.

The integral extends to infinitely high energies which in practice means that radiative corrections have to be applied properly. The absolutely normalized results of the PLUTO group are shown in Fig. 15. Outside the resonance the cross section is $R = \sigma_{tot}/\sigma_{\mu\mu} = 5.2 \pm 1.0$ in good agreement with the value of 4.7 ± 1.0 measured at 5 GeV. Note that both values include contributions from the heavy lepton τ. The 9.4 GeV value is not radiatively corrected. The results of two other experiments, the DASP2 group 61) and the DESY-Heidelberg 2 detector, which replaced the PLUTO detector after its removal to PETRA, are shown in Fig. 16. (The latter detector was operated by a DESY-Hamburg-Heidelberg-München collaboration.) Their values are not absolutely normalized. For the determination of the leptonic width Γ_{ee} both detectors used the PLUTO value of R. The results of the three experiments are summarized in Table 4.

An attempt was made by the three groups to determine the total width of the resonance. The procedure is to determine the μ pair branching ratio $B_{\mu\mu}$ on the resonance. Assuming μe universality, the total width can then be obtained as $\Gamma_{tot} = \Gamma_{ee}/B_{\mu\mu}$. In all three experiments the determination of $B_{\mu\mu}$ suffers from very low statistics. For example the PLUTO group found 60 μ pairs off resonance and 74 μ pairs on resonance 63). The angular distribution of these events is shown in Fig. 17. The data are in good agreement with the expectation of $1 + \cos^2\theta$. The values of $B_{\mu\mu}$ obtained from the three experiments are summarized again in Table 4.

Due to the large error on $B_{\mu\mu}$ only lower limits can be given on the total width of the resonance. Even if all values are combined the error is still too large to obtain a two standard deviation upper limit on the total width. Again one can only obtain a lower limit of 25 keV on a 95 % confidence level*. If we take however $B_{\mu\mu} = 2.6$ % at face value we find the 'best' value of

$$\Gamma_{tot} = 50 \text{ keV}.$$

III.C.2 Event Topology

According to common prejudice the topology of events should change drastically in the resonance region. The continuum is expected to be governed by the production of quark jets with a characterstic angular distribution of $1 + \cos^2\theta$ due to the 1/2 spin of the quarks. The resonance itself is expected to decay into gluons which then fragment into 3 jets in a disc-like configuration 64).

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* Note that this limit justifies our previous assumption $\Gamma_{ee}/\Gamma_{had} \ll 1$.

To test these theoretical conjectures we have analyzed our events in terms of sphericity. This quantity which was introduced by Brodsky and Bjorken[65)] and later used successfully in the analysis of the SLAC-LBL data[66)] is defined by

$$S = \min \left(3/2 \frac{1}{\Sigma p^2} \cdot \Sigma p_{\perp}^2\right); \quad p_{\perp} = \text{momentum perpendicular to the S-axis.}$$

The limiting values of S are 0 in the limit of two infinitely narrow jets and 1 in the limit of an isotopic event.
Also another quantity, thrust[64)] (which was first introduced by Brandt et al.[67)]) will be used. This quantity is defined as

$$T = \max \left(\frac{1}{\Sigma |p|} \cdot \Sigma |p_{\parallel}|\right); \quad p_{\parallel} = \text{momentum parallel to the T-axis.}$$

T varies between the values of 1 for two line jets and 1/2 for isotropic events. Since it turns out that the features of the data in terms of thrust and sphericity are very similar[68)] I will not discuss all aspects of both quantities. I will mostly concentrate on the sphericity, although sometimes the thrust axis will be used for convenience, because its definition is technically very simple. A word of caution should be said in this context: Although the mean angle between the jet axis defined by either S or T is zero, the distribution has a width of about 15°. This reflects the inherent uncertainty in defining the real jet axis[68)].

III.C.3 Quark Jets

The existence of jets in e^+e^- annihilation was first demonstrated by the SLAC-LBL group[66)]. Their results are shown again in Fig. 18. Their data are in good agreement with the prediction of a jet model (full curve) whereas the phase space Monte-Carlo (dashed curve) is completely ruled out at large energies. The PLUTO collaboration has done a very similar analysis[68)]. The result is presented in Fig. 19. It shows the mean observed sphericity as a function of energy over the energy range from 3 to 10 GeV. The figure shows again a dramatic fall over this energy range in good agreement with a two jet Monte-Carlo[69)] and in complete disagreement with phase space.

Note the small but significant change in sphericity at the charm threshold around 4 GeV.

The angular distribution of the jet axis is shown in Fig. 20. Data are in good agreement with the theoretical expectation for spin 1/2 quark jets. A fit to the data with $1 + \alpha \cos^2\theta$ gives the values of $\alpha = 0.76 \pm 0.3$ at 7.7 GeV and 1.63 ±0.6 at 9.4 GeV. Two other interesting properties of these jets can be read from Fig. 21. It shows the energy distribution of both charged and neutral energy with respect to the thrust axis for three different thrust intervals. The first observation is that the neutral energy flow follows almost exactly the energy flow of the charged particles. The relative partition of neutral to charged energy can be determined from this figure to be about 0.8. Furthermore the half opening angle of the jets turns out to be of the order of 30^0. A similar result is obtained, if one compares the mean momenta perpendicular and parallel to the jet axis.

Many observations on jets are best demonstrated looking at a typical event shown in Fig. 22. To summarize, there is clear (confirming) evidence for two jets in e^+e^- annihilation, the sphericity decreasing with increasing energy. The angular distribution of these jets is compatible with the quark spin being 1/2. Neutral and charged energy in these jets are strongly correlated and subtend a half opening angle of about 30^0.

III.C.4 Change of Topology at the Ypsilon

Whereas off resonance only quark pair production is at work, the on resonance cross section is composed of three different processes, as shown in Fig. 23. Since we are interested in the direct decay mechanism, the off resonance and the vacuum polarization terms have to be subtracted in all distributions. The latter, which is proportional to $R \cdot B_{\mu\mu}$ represents about 13 % of the resonance cross section. Fig. 24 shows again the mean observed sphericity over the full energy range including now the Y region. We notice a strong rise of the sphericity as we go across the resonance (inset of the figure). This increase gets even more pronounced if we extract the direct decay term as indicated above.

This value comes in fact very near to the value predicted by Hagiwara assuming a three gluon jet decay of the Ypsilon ('QCD' prediction)[70]. Note however that in terms of sphericity there is only very little difference between the phase space and the QCD prediction.

The features of these data change very little if we take thrust instead of sphericity. Fig. 25 shows a distribution of (1 - the mean observed thrust) over the same energy range. Again there is a dramatic change of topology in the Y region and the direct term gets very close to the QCD prediction of Koller, Walsh and Krasemann$^{71)}$ of <T> = 0.75. However, the value is again very close to the phase space prediction.

The fact that the QCD and phase space predictions are so similar may be surprising at first sight, since one expects isotropic events in phase space and disc-like events in QCD. However, at the low multiplicities encountered here phase space is not at all isotropic and the definition of sphericity and thrust always tends to find a planar structure in the events. On the other hand we are dealing with 3 GeV gluon jets in QCD which may be very broad jets and hence the disc structure is smeared out. These features have been discussed in detail by G. Alexander in the parallel session$^{68)}$. Note also that the sphericity and thrust values are not corrected for acceptance and one has to be cautious in comparing them directly with the prediction. Acceptance corrections are however not expected to be very large.

The previous two figures showed a strong change of events topology in the charged energy flow. Fig. 26 shows a complementary observation of the DESY-Heidelberg 2 group who have measured the distribution of the neutral sphericity and compared the differential sphericity off and on resonance$^{62)}$. A striking difference is seen in the two distributions, the mean value changing from <s> = 0.19 to <s> = 0.37 with an error of 0.02 which is again very close to the QCD prediction of <s> = 0.4 $^{70)}$.

III.C.5 Other Properties of Events in the Ypsilon Region

A surprising observation$^{72)}$ which all three groups agree on is the relatively small change in mean multiplicity as one passes from the continuum to the resonance. Fig. 27 shows the distribution of observed charged multiplicity on and off resonance for the DESY-Heidelberg 2 detector. The mean charged multiplicity changes from 6.4 off resonance to 7.3 on resonance (error 0.2) including the correction for non direct terms$^{62)}$. A very similar increase of about one unit is also found by the PLUTO$^{63)}$ and the DASP 2 collaborations$^{61)}$.

The last piece of information I want to mention is from the PLUTO group who measured the inclusive K^0 production in the 9.5 GeV energy region[63]. Their result for the visible cross section is displayed in Fig. 28 as a function of energy. For comparison the total cross section is indicated by a dashed curve in the same figure with arbitrary normalization.

The comparison shows that the K_S^0 production follows about the trend of the total cross section. Quantitatively the comparison of on and off resonance cross section yields a ratio of 4.0 + 1.7 for K^0 production, whereas it is about 2.5 for the total cross section. They conclude therefore that there is no significant change of K_S^0's produced per event if one goes through the resonance region.

III.C.6 Ypsilon Summary

In summary we have seen that the Y is produced in e^+e^- annihilation with a mass of 9.46 ± 0.01 GeV, a leptonic width of $\Gamma_{ee} = 1.2 \pm .2$ keV, a branching ratio $B_{\mu\mu} = 2.6 \pm 1.4$ % and a total width of more than 25 keV (best value 50 keV). These parameters strongly suggest that the Ypsilon is a quark antiquark bound state with a quark charge of 1/3. Further observations in the resonance region are: a considerable change of topology from a 2 jet structure outside the resonance to a more isotropic structure at the Y, a small increase of the charged multiplicity by about 1 unit as one goes from off to on resonance and no large change of the K_S^0 content per event. A quantitative analysis of the change of topology in terms of thrust and sphericity shows that the change in the Y region is about as expected from QCD (change from a 2 quark jet to a 3 gluon jet structure). However, the proximity of phase space does not allow a firm conclusion on the existence of gluon jets.

III.C.7 Ypsilon Prime

During the last weeks before the conference the DASP 2[61,73] and the DESY-Heidelberg 2[62,74] groups proceeded into the region of 10 GeV to search for the first excitation in the Y family (Y') suggested by the data of the Columbia-Fermilab-Stony Brook collaboration. Fig. 29 shows their result. There is a resonance structure around 10.02 GeV with a width compatible with the resolution of the e^+e^- machine DORIS. In Table 5 the parameters of the Y' as found by the two groups are compiled together with the mean values. The first surprising feature of these data is the relatively low mass difference between Y and Y'. Fig. 30 compares the FNAL and DESY data. The value is lower than the one suggested by the Columbia-Fermilab-Stony Brook collabroation and in particular $\Delta M(\Upsilon) = 558 \pm 10$ MeV is smaller than $\Delta M(\psi) = 589 \pm 1$ MeV. This value for the mass difference gives increasing evidence for the existence of a second exited state (Υ") below threshold[56,57]. As we heard in J. Rosner's talk the low value of Γ_{ee} at the Υ' eliminates the last doubt about the identiy of the component quark[75]. It is the 'beauty' quark with a charge of 1/3.

IV. CONCLUSION

To conclude let me return to Fig. 1. We heard in the preceeding talk that there is overwhelming evidence now for the existence of a new heavy lepton and most probably also for its own neutrino. If we look into the quark sector symmetry seems to prevail. In addition to the charm quark there is now ample evidence for the existence of a new heavy quark which is most probably of the 'beauty' type. To answer the question whether a 6th quark t would constitute perfect symmetry between leptons and quarks again our answer can now only be:

PETRA works and CESR and PEP will follow soon!

Acknowledgement

I am indebted to L. Montanet, V. Hepp, B. French, J. Six, B. Pietrzyk, D. Treille, Chan Hong-Mo, H. Høgaasen, and V. Hungerbühler for many discussions and hints on the subjects of chapter II. I also want to express my gratitude to G. Feldman, G. Alexander, J. Bienlein, R. Devenish, G. Heinzelmann, K. Koller, H. Meyer, G. Mikenberg, H. Rubinstein, W. Schmidt-Parzefall, B. Stella, H. Spitzer, T. Walsh, G. Wolf, and all my colleagues at DESY who helped me in the preparation of this talk. I am particularly grateful to my scientific secretaries Y. Sumi and H. Suda for their continuous support during the conference.

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Table 1: Broad baryonium candidates.
Masses and widths are given in MeV, the latter in brackets.
Quantum numbers are indicated as far as they are known

1 9 7 4		N E W		
$\bar{p}p$ total 8,13,14)	$pp \rightarrow \pi^+\pi^-$ 9)	$\bar{p}p \rightarrow K^+K^-$ 10)	$\bar{p}p \rightarrow \pi^o\pi^o$ 11)	$\pi^-p \rightarrow \bar{p}pn$ 12)
	2480± 30 (280± 25) $J^{pc} = 5^{--}$, I=1	also I = 0		
'U': 2350± 15 (160± 20) I = 0,1	2310± 30 (210± 25) $J^{pc} = 4^{++}$, I=0			~ 2300 (200÷300) $J^P = 4^+$
'T': 2190± 10 (90± 20) I = 1	2150± 30 (200± 25) $J^{pc} = 3^{--}$, I=1	also I = 0	2150± 10 (250± 10) $J^P = 2^+$	~2100 (200÷300) $J^P = 3^-$
				[~2000 (~150) $J^P = 2^+$]
'S': 1936 ± 1 ($\lesssim$ 10) I = 1, (0)				~ 1950 (200÷300) $J^P = 1^-$

Table 2: Narrow baryonium candidates

Mass (MeV)	Width (MeV)	seen in reaction	Ref.	Status
2950 ± 10	$\lesssim$ 15	$\pi^- p \to \pi^- p_f \bar{p} + X$	19,20	?
2204 ± 5	16^{+20}_{-16}	$\pi^- p \to \pi^- p_f p\bar{p}$	21,22, 23,24	confirmed, although with low statistical significance
2020 ± 3	24 ± 12			
1936 ± 1	$\lesssim$ 10	$\bar{p}p$: 'S' resonance	13 , 14	well established

Table 3: Branching ratios of P_c/χ states.
$BR(\psi' \to \gamma\chi) \cdot BR(\chi \to \gamma\, J/\psi)$ in %. Upper limits 95 % C.L.

State	Status	DASP[45]	DESY-HD[41] NEW VALUES !	MPPSSSD[42]	SLAC-LBL[43]	PLUTO[44]
$\chi(3.41)$	o.k.	0.3 ± 0.2	< 0.25	3.3 ± 1.7	0.2 ± 0.2	$1.2 \pm^{0.9}_{0.6}$
$\chi(3.45)$	?	< 0.5	< 0.2	< 2.5	0.8 ± 0.4	$0.7 \pm^{0.8}_{0.5}$
$\chi(3.51)$	o.k.	2.1 ± 0.4	2.5 ± 0.4	5.0 ± 1.5	2.4 ± 0.8	$1.2 \pm^{1.0}_{0.6}$
$\chi(3.55)$	o.k.	1.6 ± 0.4	1.0 ± 0.2	2.2 ± 1.0	1.0 ± 0.6	$0.9 \pm^{1.0}_{0.5}$
(3.59)	?		0.18 ± 0.06			

Table 4:

Results on Υ(9.46)					
	$M(\Upsilon)$ (GeV)	Exp.Width (MeV)	$\Gamma_{ee}(\Upsilon)$ (keV)	$B_{\mu\mu}$ (%)	Γ_{tot} (keV)
PLUTO	9.46 ± 0.01	18 ± 2	1.3 ± 0.4	2.7 ± 2.0	>20 (2s.d.)
DASP II	9.46 ± 0.01	18 ± 2	1.5 ± 0.4	2.5 ± 2.1	>20 (2s.d.)
D-H II	9.46 ± 0.01	17 ± 2	1.04 ± 0.28	$1.0^{+3.4}_{-1.0}$	>15 (2s.d.)

Mean Values

$\Gamma = (1.2 \pm 0.2)$ keV

$B_{\mu\mu} = (2.6 \pm 1.4)$ %

$\Gamma_{tot} > 25$ keV (95% c.l.)

(Best value $\Gamma_{tot} = 50$ keV)

Table 5:

Results on Υ'(10.02)				
	$M(\Upsilon')$ (GeV)	$M(\Upsilon')-M(\Upsilon)$ (MeV)	$\Gamma_{ee}(\Upsilon')$ (keV)	$\frac{\Gamma_{ee}(\Upsilon)}{\Gamma_{ee}(\Upsilon')}$
DASP II	10.012 ± 0.020	555 ± 11	0.35 ± 0.14	4.3 ± 1.5
D-H II	10.02 ± 0.02	560 ± 10	0.32 ± 0.13	3.3 ± 0.9
Mean	10.016 ± 0.020	558 ± 10	0.33 ± 0.10	3.6 ± 0.8

$$M(\Upsilon') - M(\Upsilon) < M(\psi') - M(J/\psi)$$

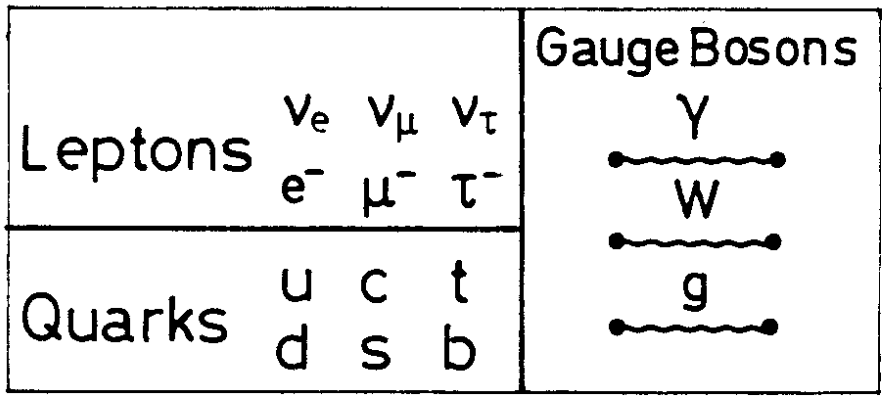

Fig. 1: Common belief on quarks, leptons and their mutual interactions.

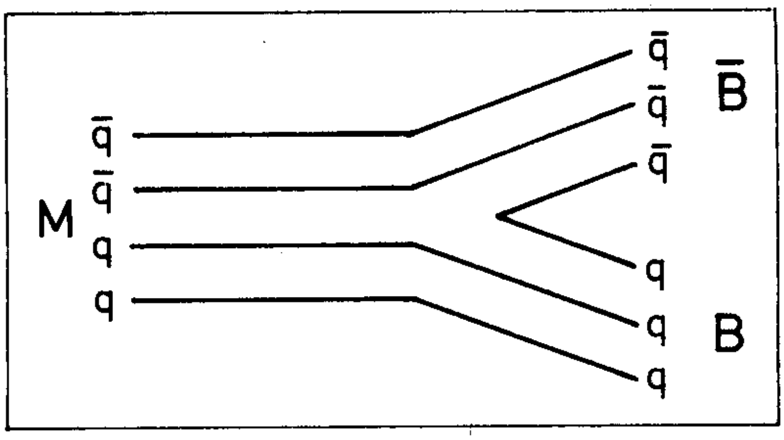

Fig. 2: Baryonium decay

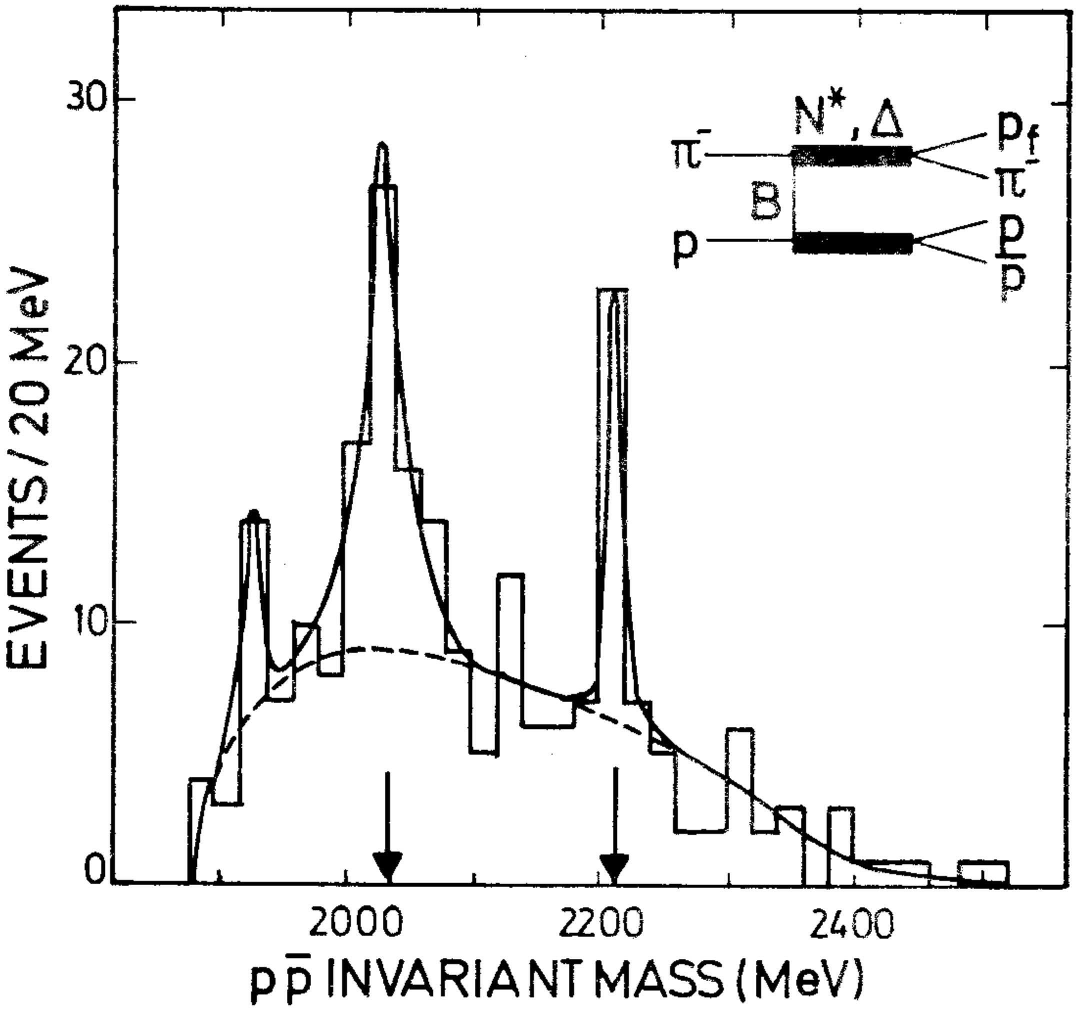

Fig. 3: CERN-College de France-Ecole Polytechnique-Orsay Collaboration: Backward ($\bar{p}p$) mass distribution in the reaction $\pi^- p \to \pi^- p\bar{p}p$ exhibiting two narrow peaks at 2.02 and 2.20 GeV. 9 and 12 GeV data with selection on Δ and $\cos\Theta^*(p,p) < 0$ are shown.

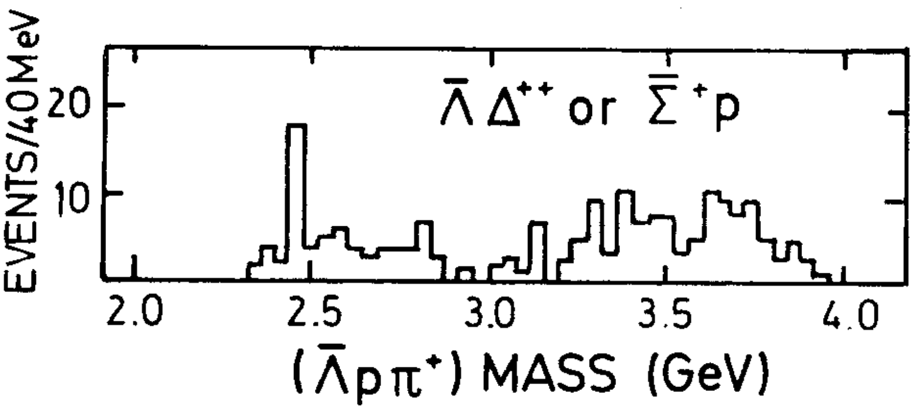

Fig. 4: Glasgow-DESY Collaboration: ($\bar{\Lambda}p\pi^+$) mass distribution in the reaction $K^+p \to \bar{\Lambda}p\pi^+n$ with an indication of a peak at 2.46 GeV.

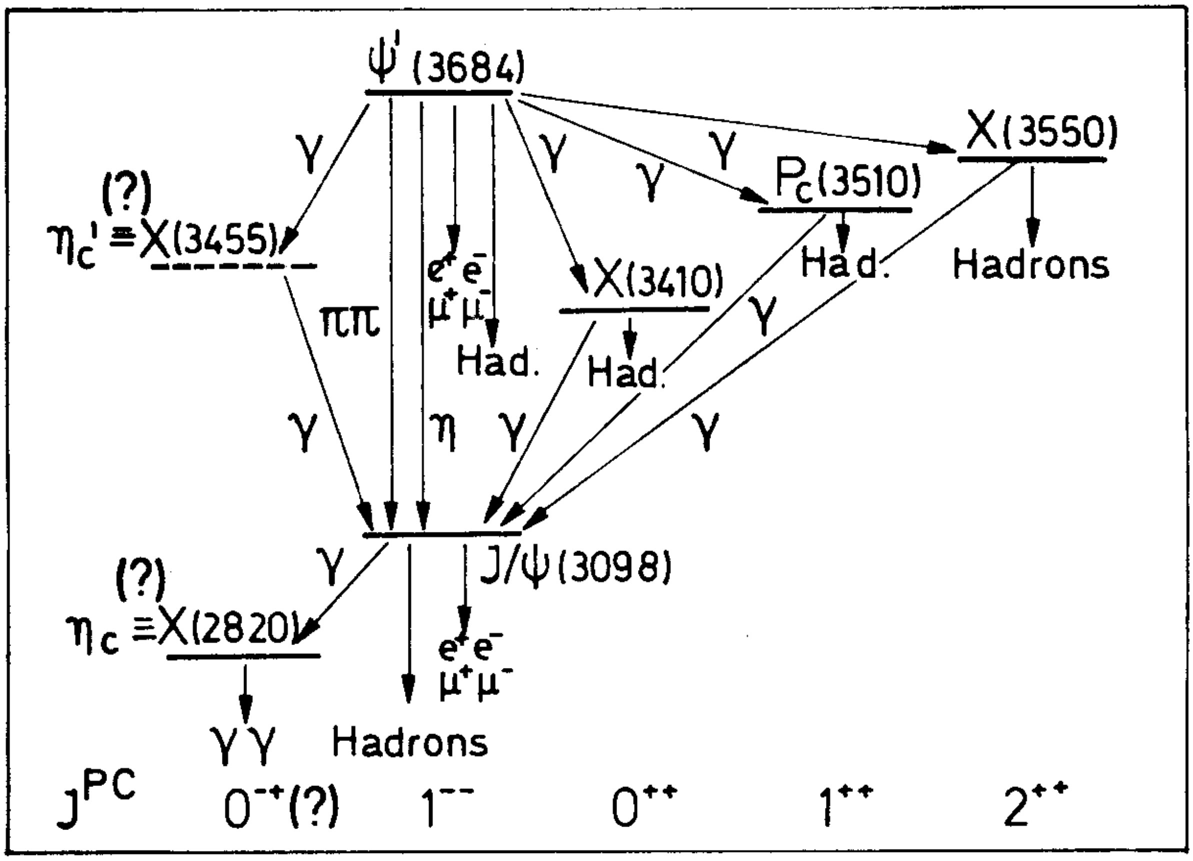

Fig. 5: The experimental knowledge on the charmonium states (1977).

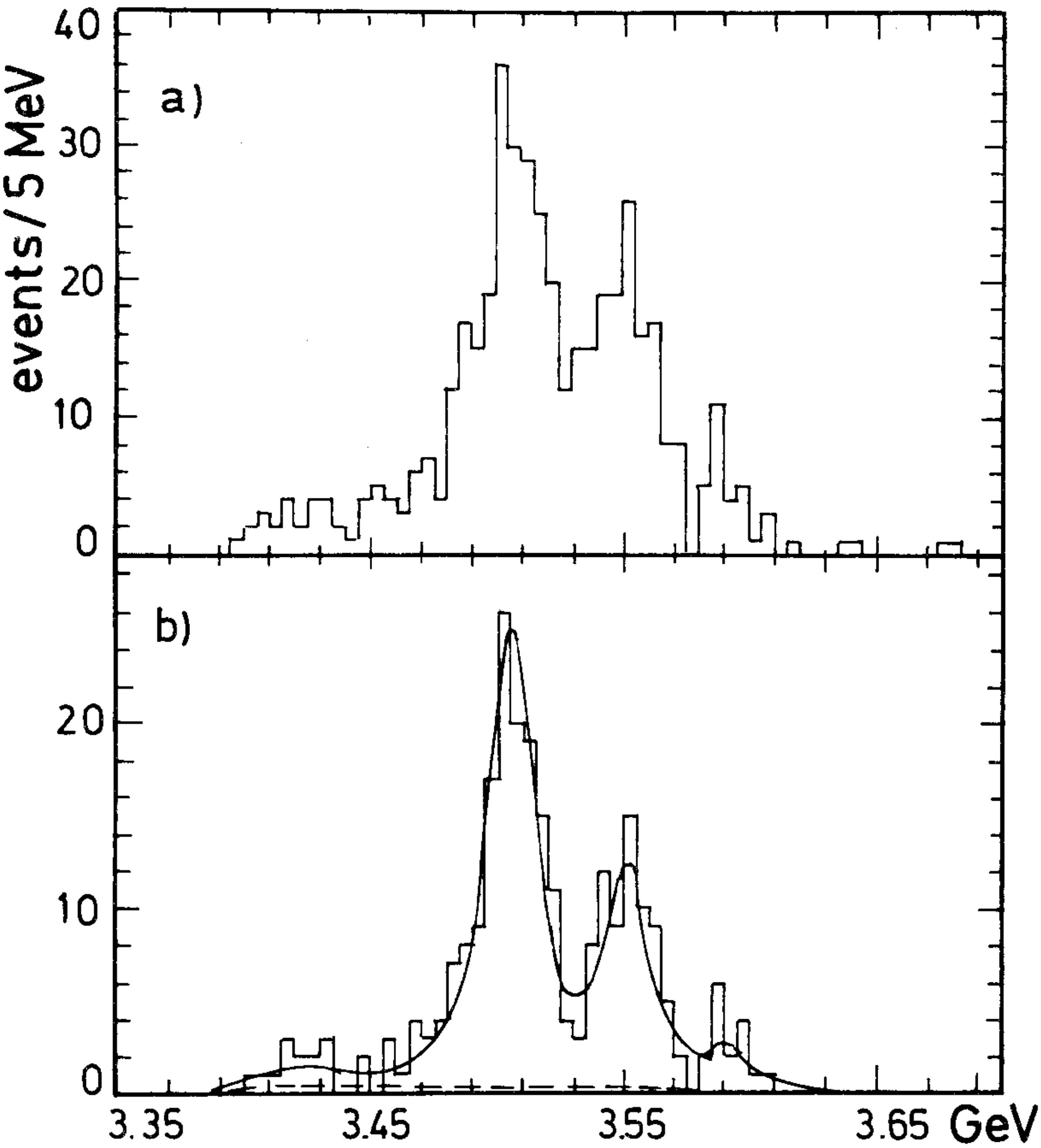

Fig. 6: DESY-Heidelberg Collaboration: High mass solution of the (γ J/ψ) system in the decay $\psi' \rightarrow \gamma\gamma J/\psi$. Note the excess of events at 3.6 GeV. (a) Two photon mass less than 520 MeV. (b) In addition, photon angular error less than 200 mrad.

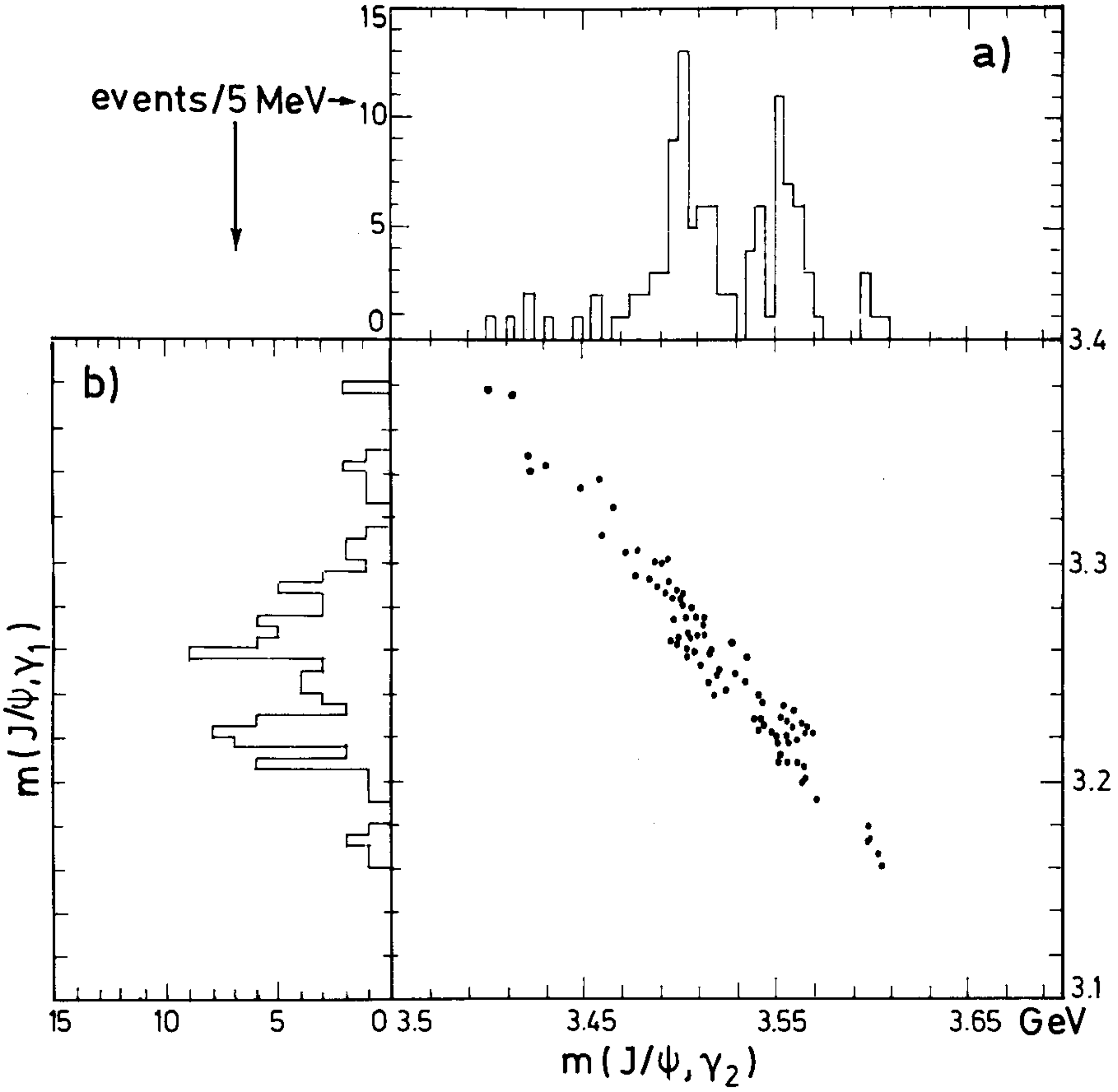

Fig. 7: DESY-Heidelberg Collaboration: High versus low mass solution of the (γ J/ψ) system in the decay $\psi' \to \gamma\gamma J/\psi$. Only events with converted photons.

(a) high mass solution

(b) low mass solution

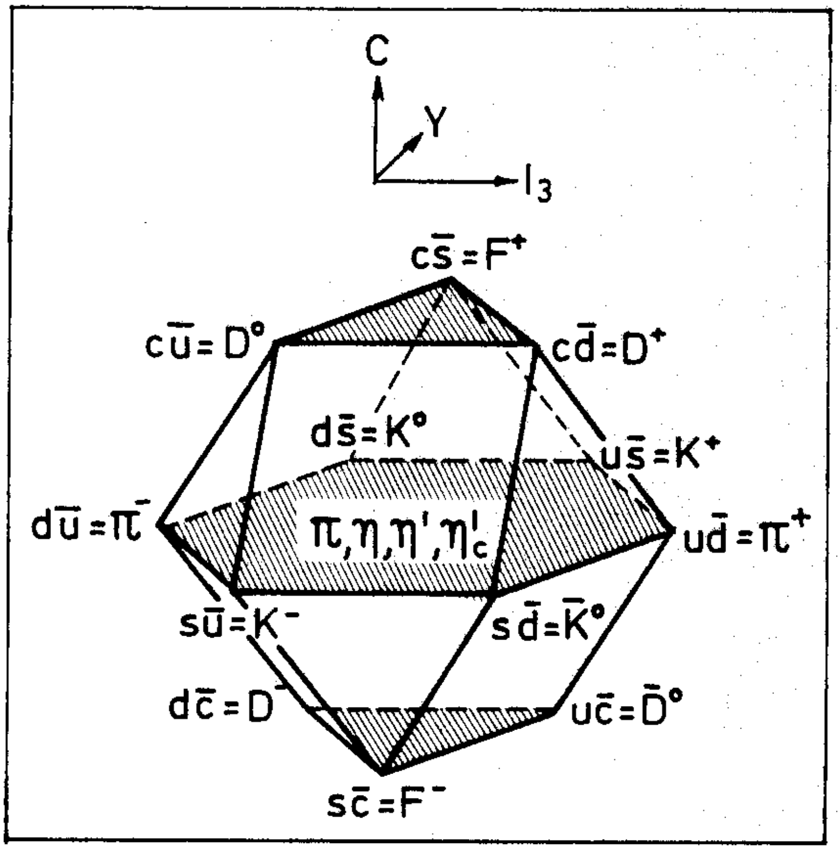

Fig. 8: The multiplet of pseudoscalar mesons in SU(4)

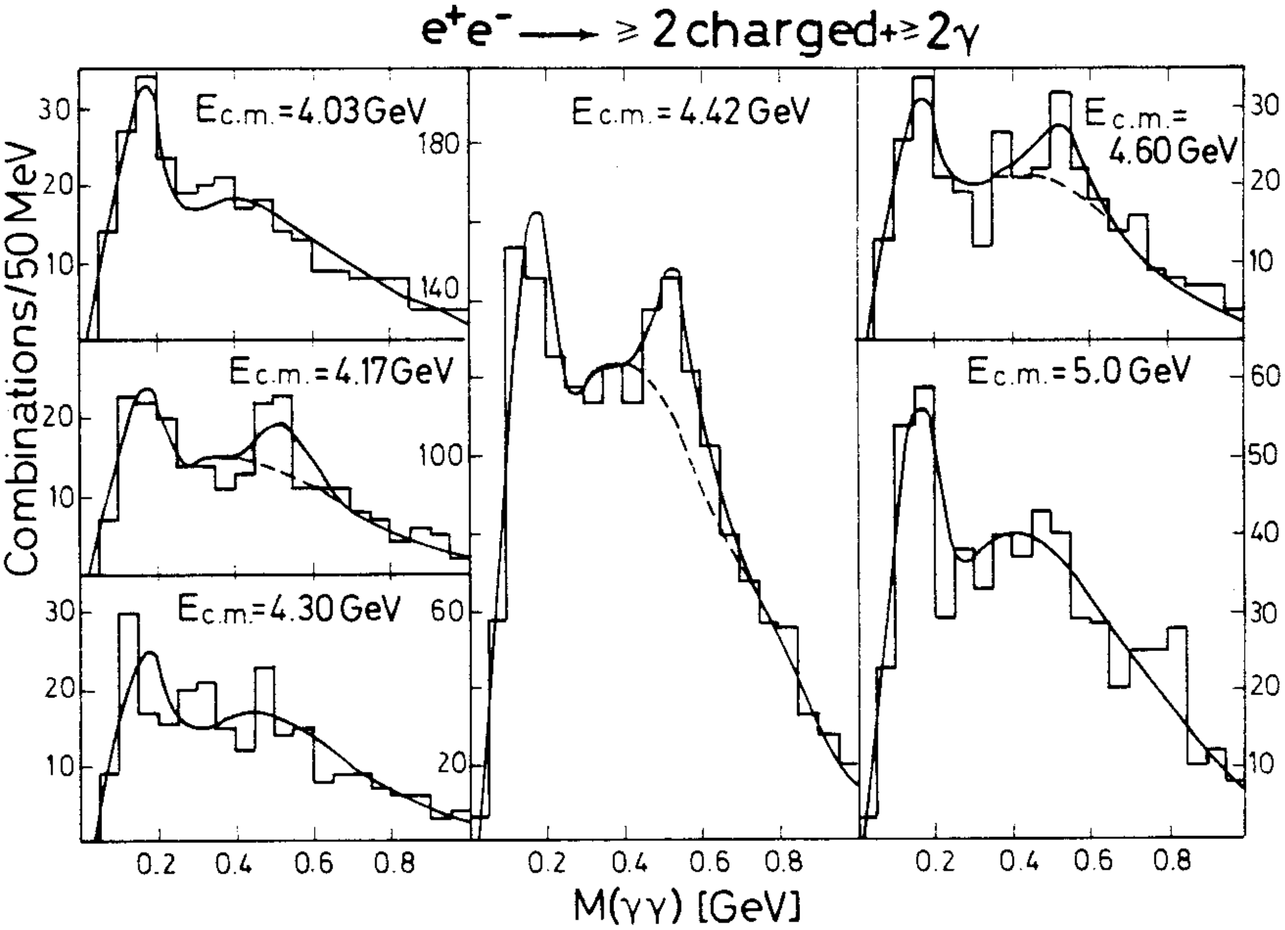

Fig. 9: DASP Collaboration: Inclusive η production in e^+e^- annihilation in the 4 to 5 GeV energy range

(a) Two photon mass distribution in different energy intervals. The full curve is the sum of the combinatorial background (photons taken from different events) and a fit to the π^0 and η. The dashed curve represents the background without η production.

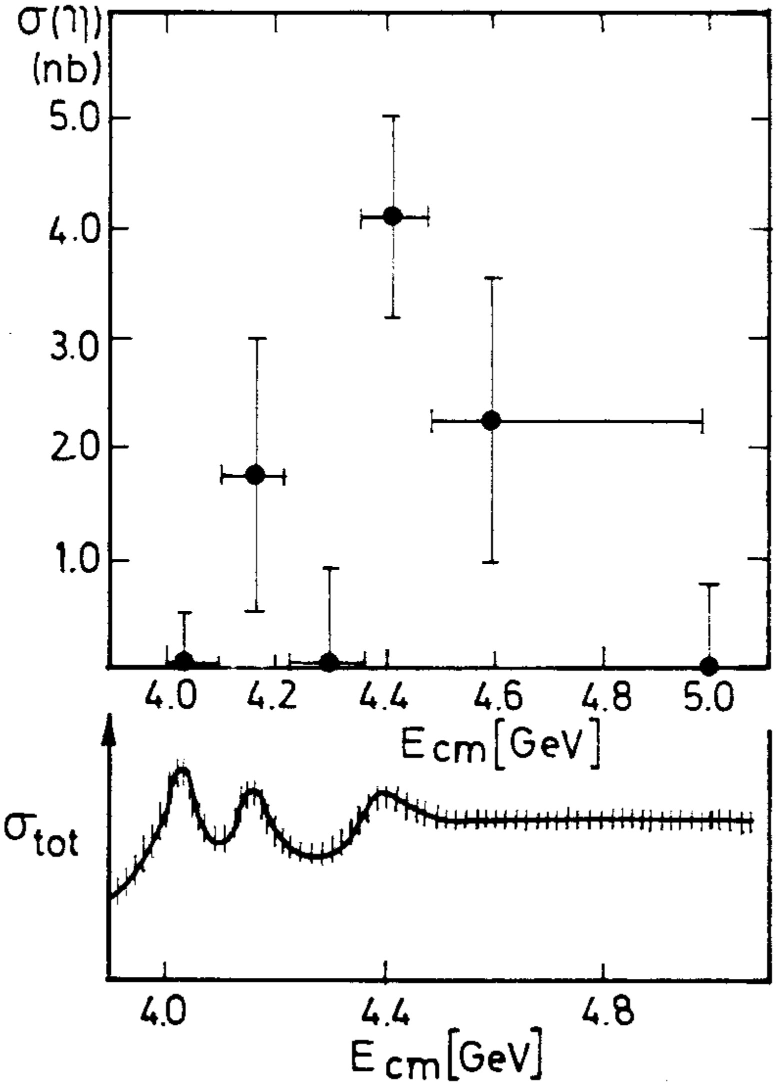

Fig. 9: DASP Collaboration: Inclusive η production in e^+e^- annihilation in the 4 to 5 GeV energy range

(b) Inclusive cross section for η production as a function of energy. The trend of the total cross section is given for comparison.

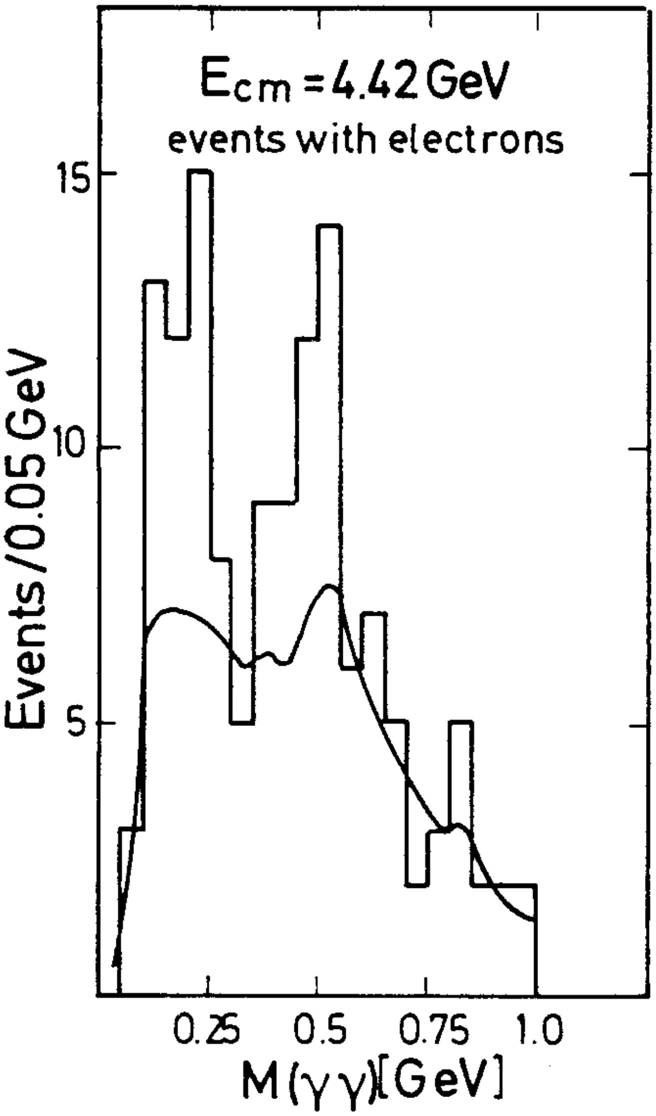

Fig. 10: DASP Collaboration: Two photon mass distribution of events including electrons in the 4.42 GeV energy region. The full curve indicates the background from misidentified electron.

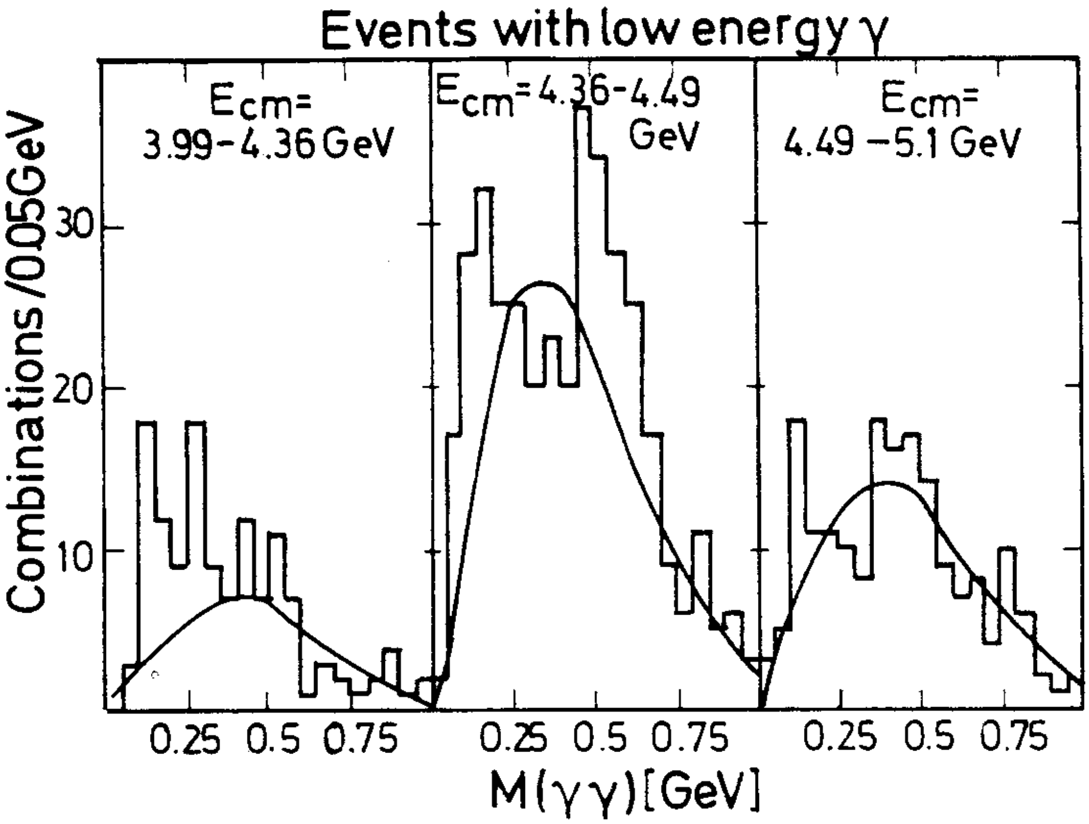

Fig. 11: DASP Collaboration: Two photon mass distribution of events including an additional low energy photon in three different energy intervals (E_γ < 200 MeV).

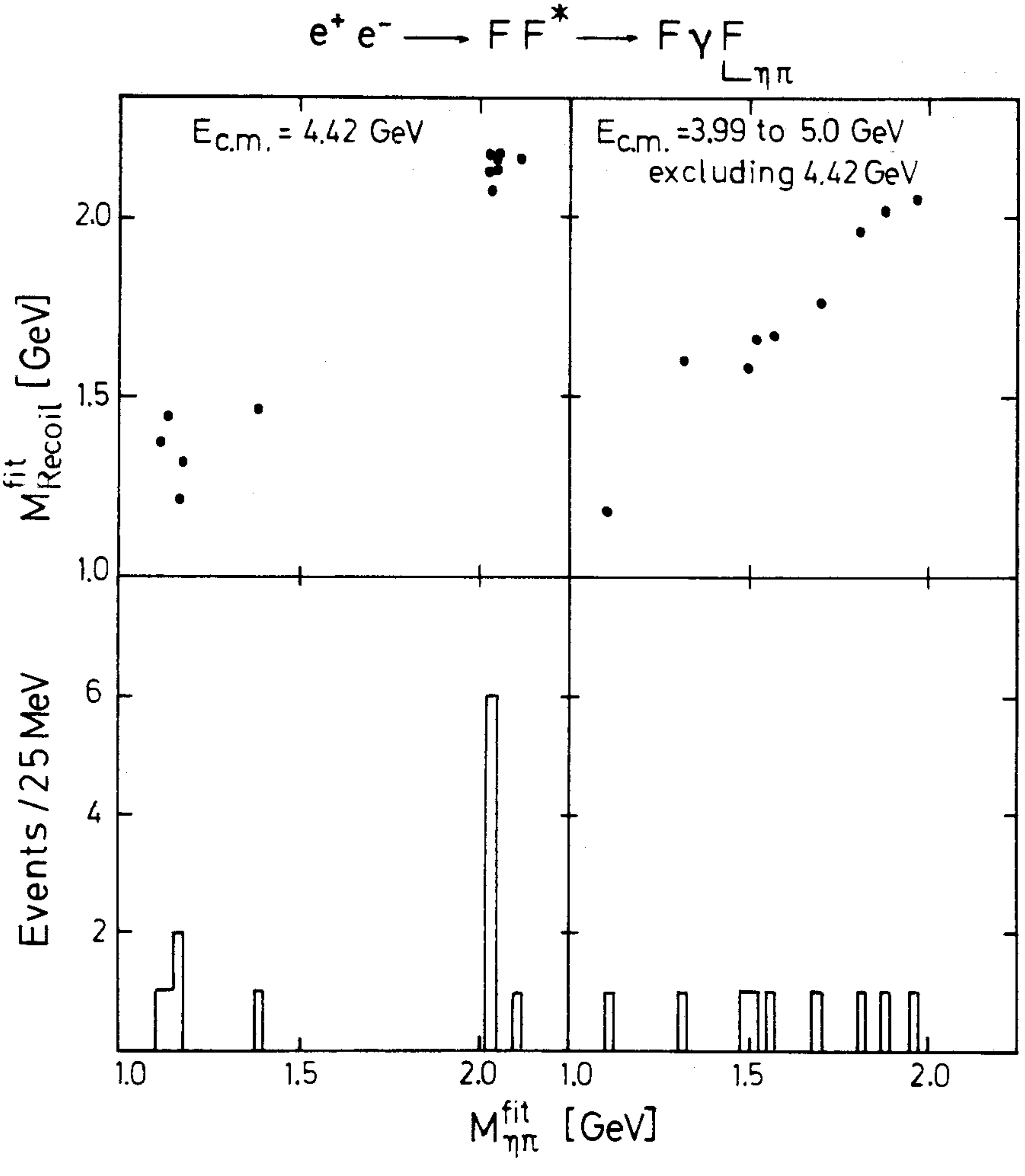

Fig. 12: DASP Collaboration: Events from the reaction $e^+e^- \to \eta\pi\ \gamma_{soft} + X$ at 4.42 GeV and excluding 4.42 GeV. A fit assuming $e^+e^- \to FF^*$; $F^* \to \gamma F$, one $F \to \eta\pi$ is applied. The figure shows biplots of the fitted $\eta\pi$ mass distribution against the recoil mass and $\eta\pi$ distributions for events with $\chi^2 < 8$ and a $\pi\eta$ mass difference $|M_{fit} - M_{meas}| < 250$ MeV.

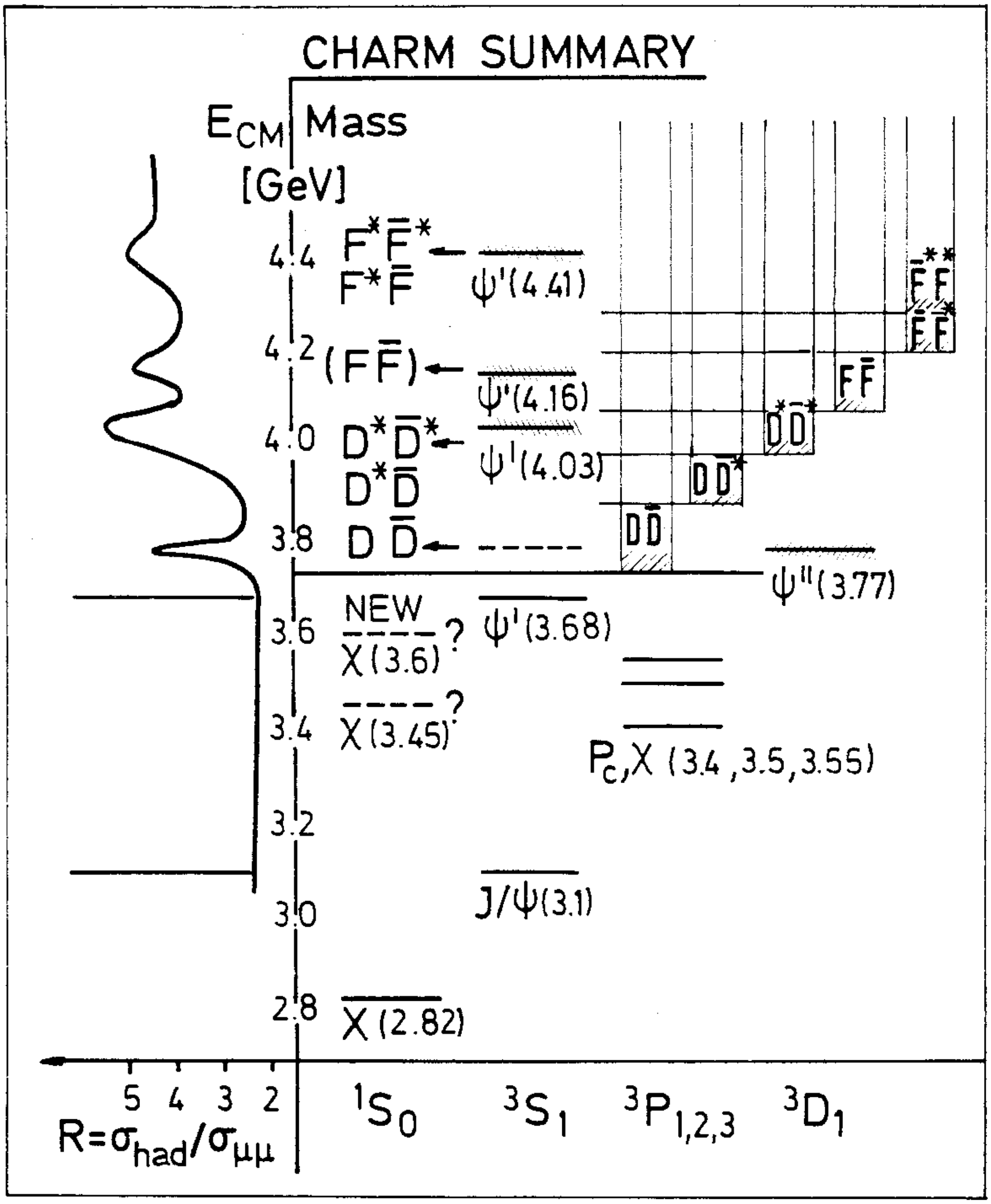

Fig. 13: Schematic summary of the experimental situation on charm.

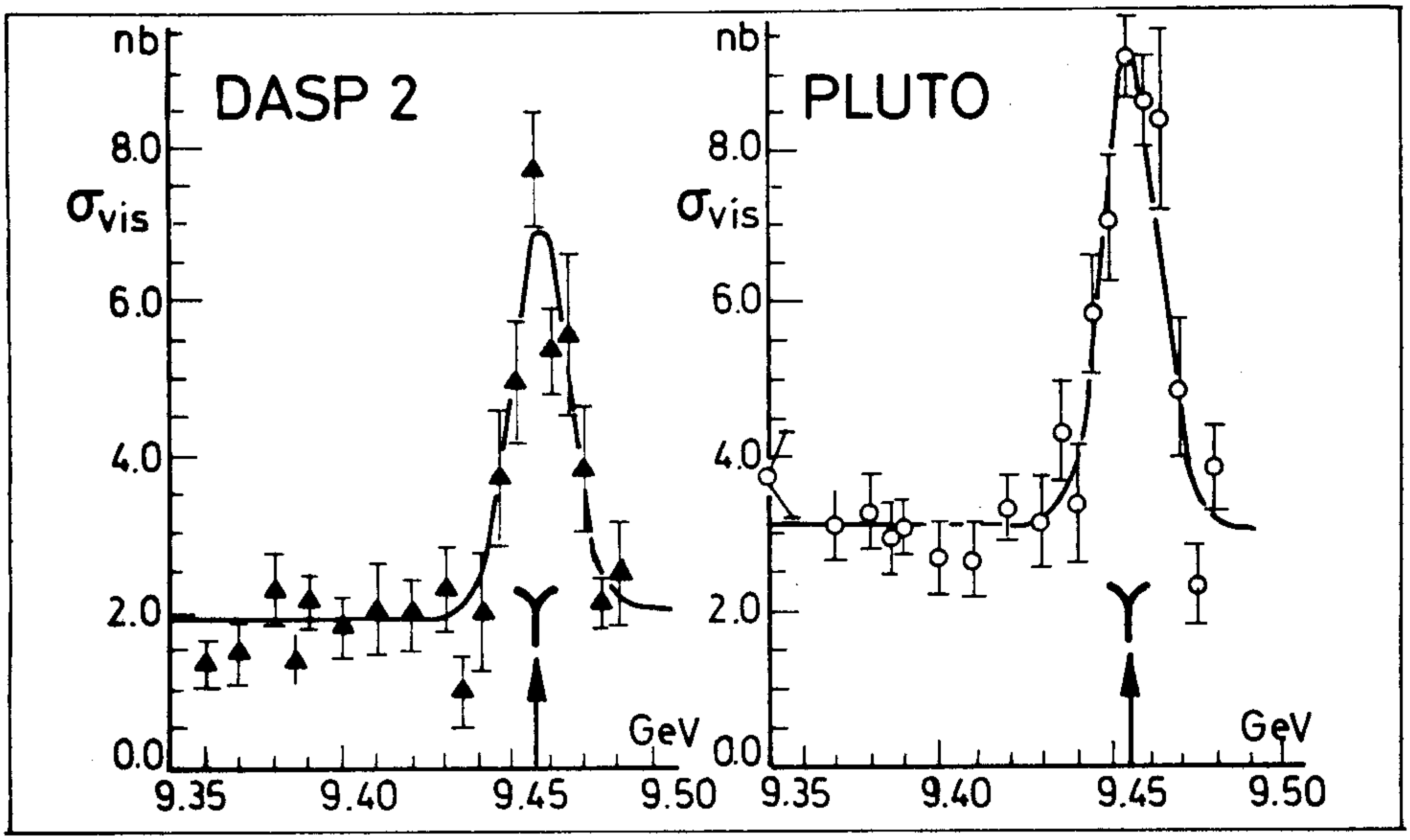

Fig. 14: PLUTO and DASP 2 Collaborations: The original evidence for Υ production in e^+e^- annihilation .

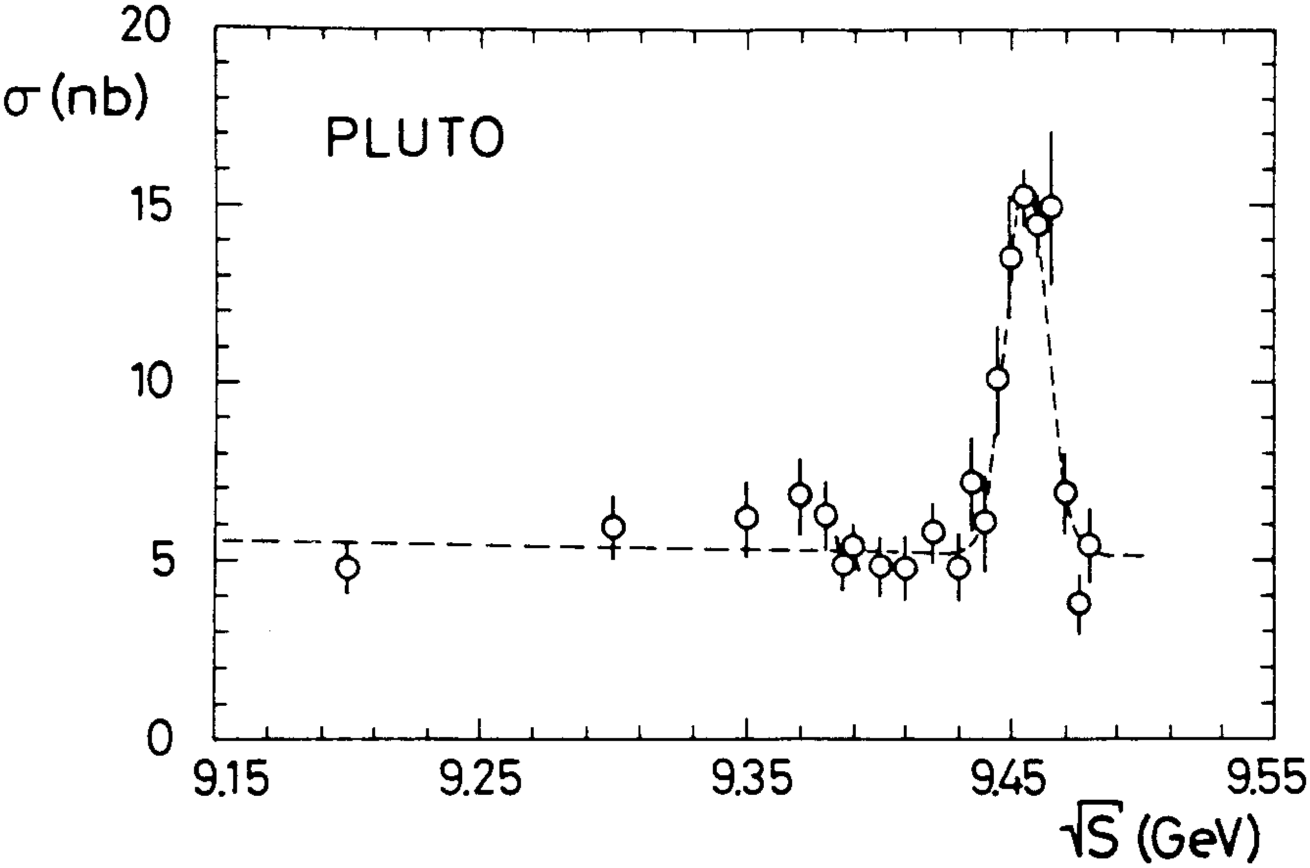

Fig. 15: PLUTO Collaboration: Absolutely normalized hadronic cross section in the Υ region.

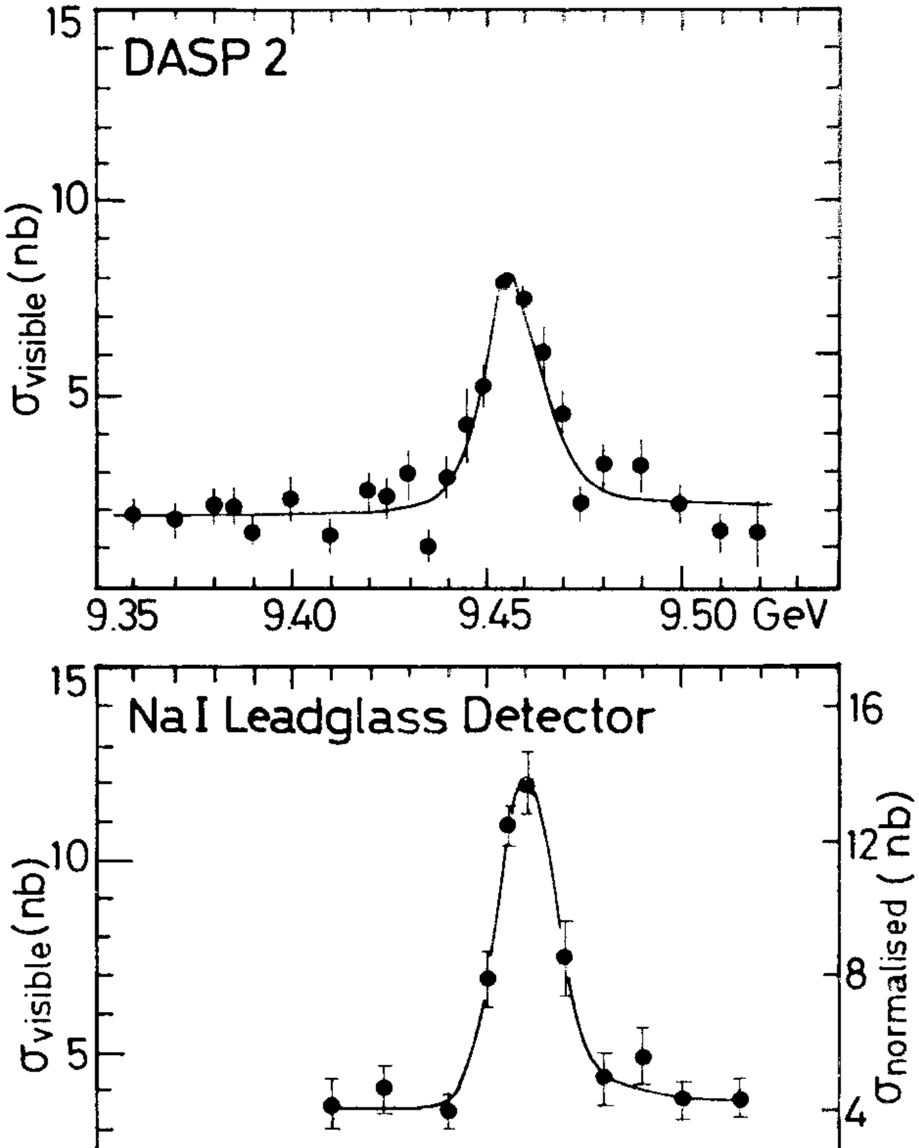

Fig. 16: DASP 2 and DESY-Hamburg-Heidelberg-München Collaboration: Visible cross section for $e^+e^- \to$ hadrons in the Υ region.

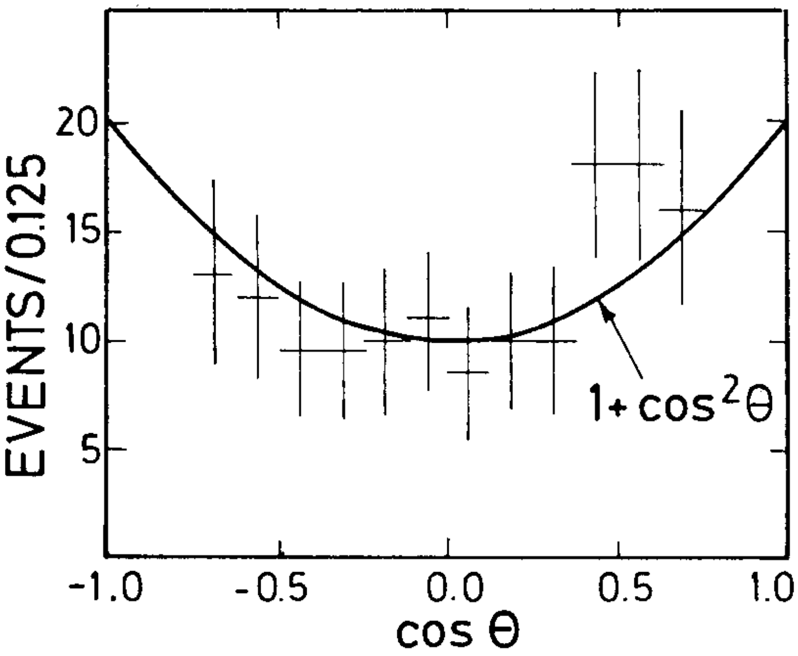

Fig. 17: PLUTO Collaboration: Angular distribution of muon pairs produced in the Y region. Data on and off resonance are combined.

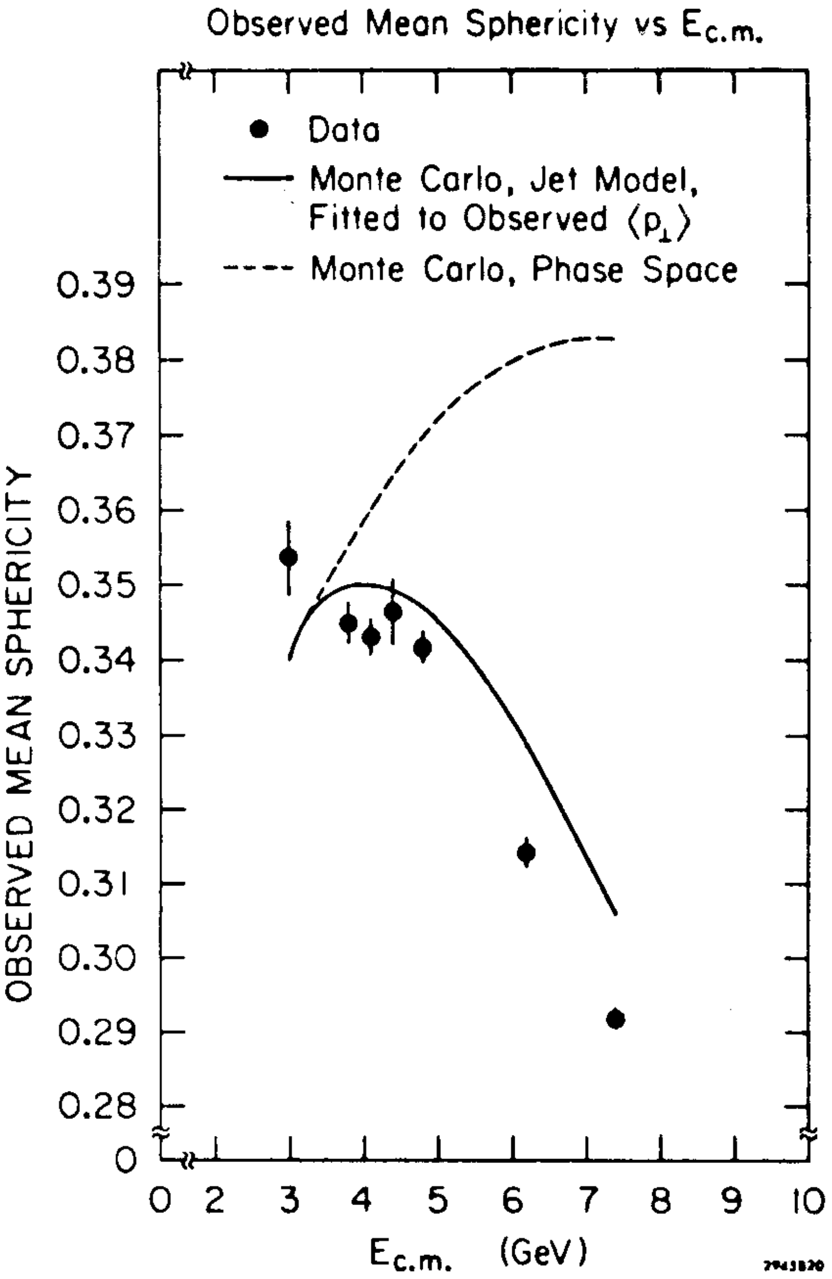

Fig. 18: SLAC-LBL Collaboration: First evidence for jets in e^+e^- annihilation. Observed mean sphericity as a function of energy. The full and dashed line show Monte-Carlo simulations of a jet and phase space model, respecticely.

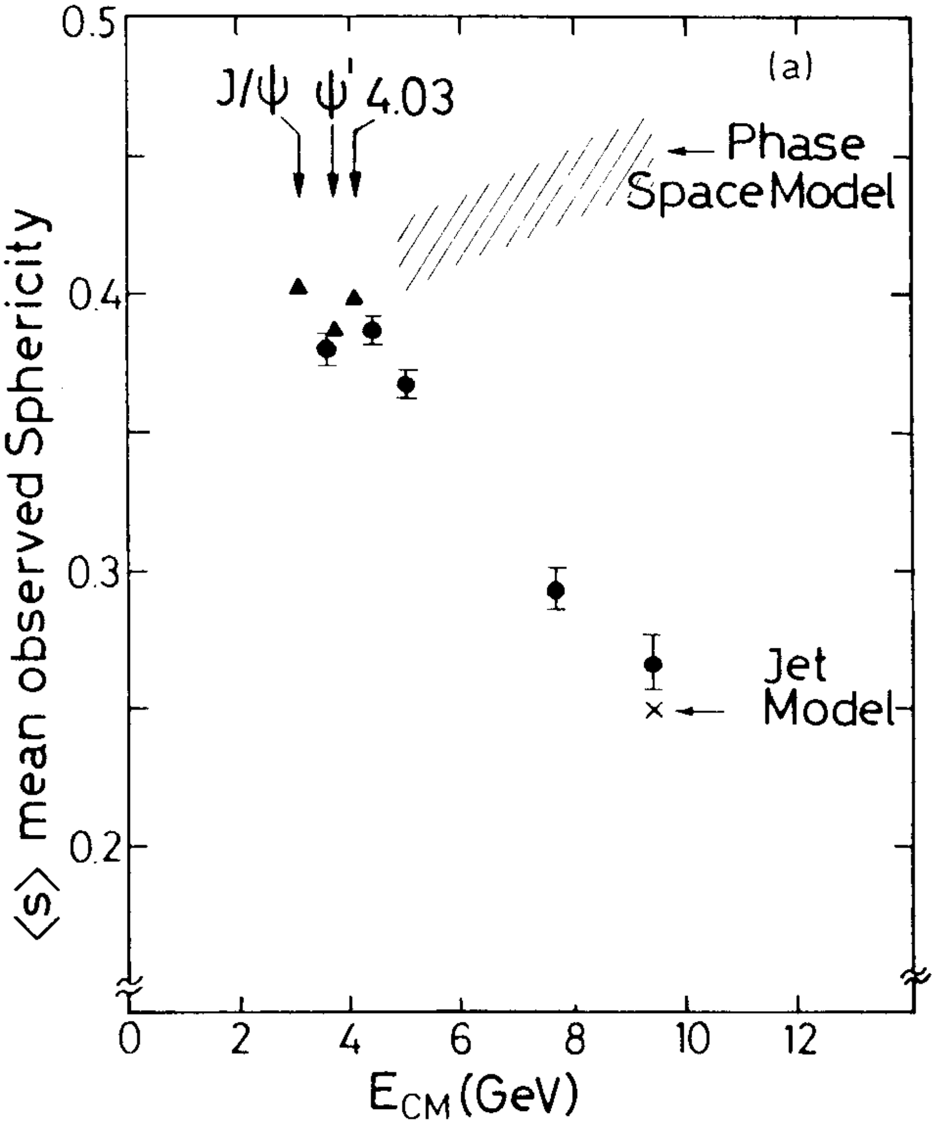

Fig. 19: PLUTO Collaboration: Observed mean spericity of charged particles ($\geq$ 4 prongs) as a function of energy. The shaded region represents the phase-space prediction, the cross the one for two jets[69].

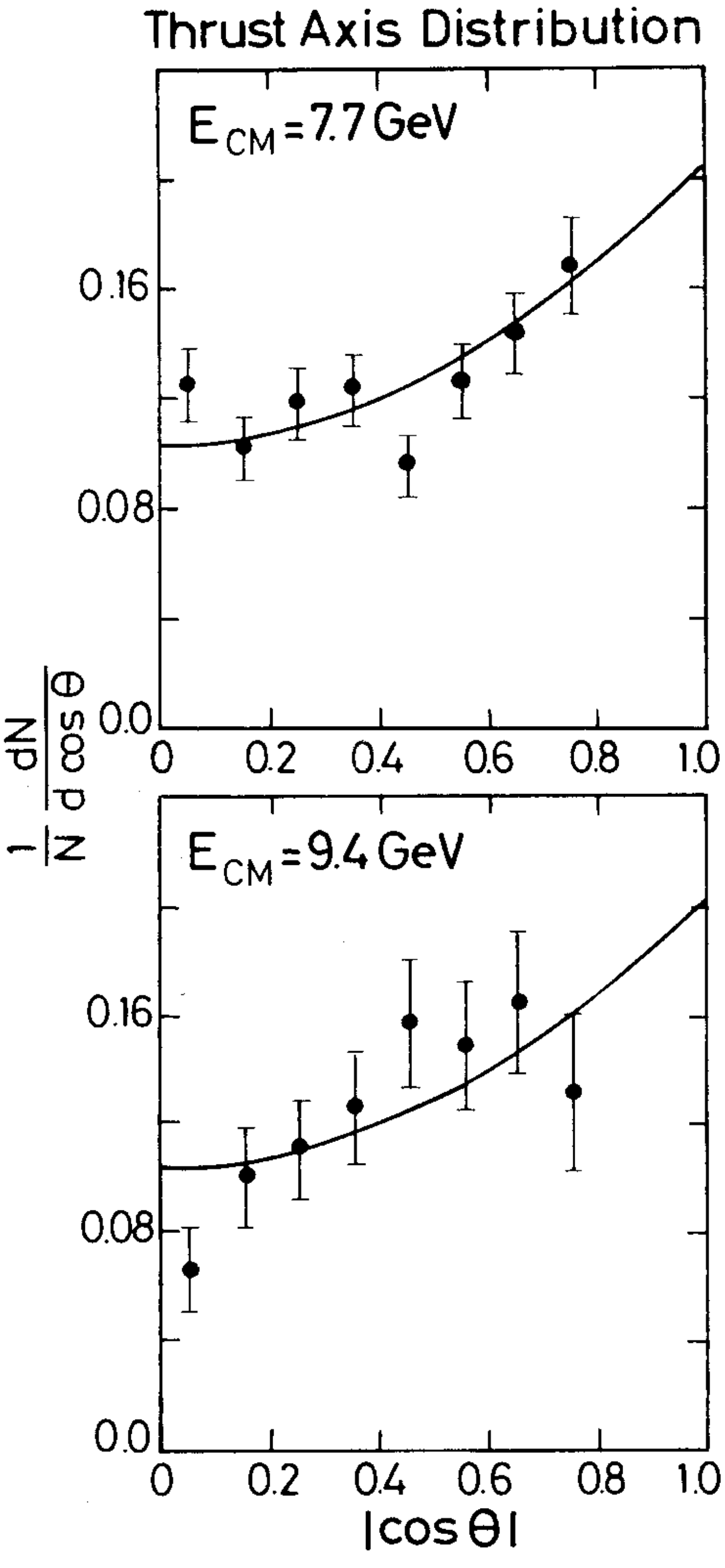

Fig. 20: PLUTO Collaboration: Angular distribution of the jet axis as defined by thrust for two CM energies.

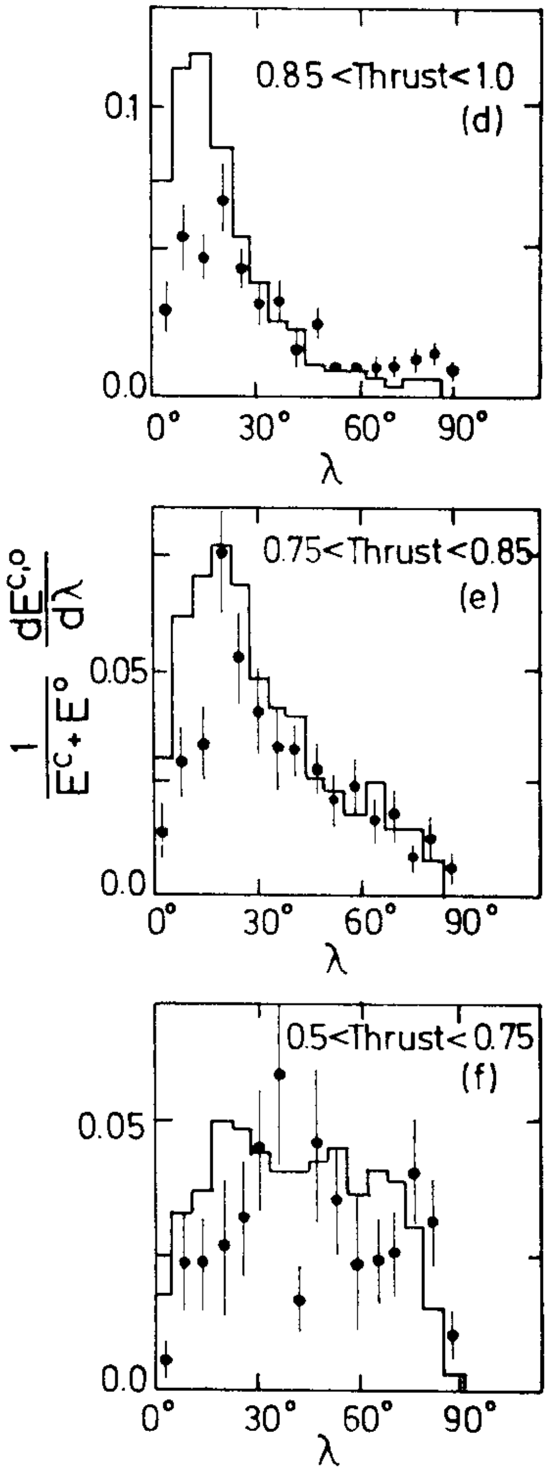

Fig. 21: PLUTO Collaboration: Angular distribution 1/E dE/dλ of neutral (data points) and charged (histogram) energy with respect to the thrustaxis for three different thrust intervals. λ is the angle between the momentum vector and the thrustaxis.

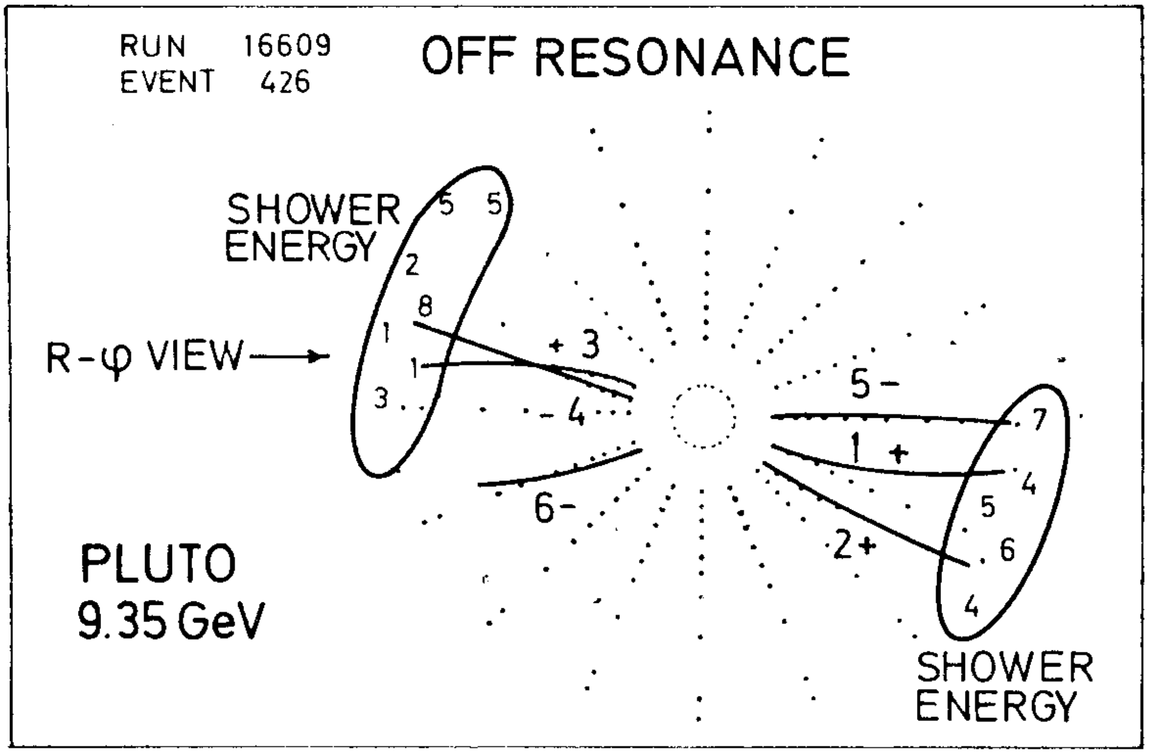

Fig. 22: PLUTO Collaboration: A typical two jet event at 9.35 GeV C.M. energy.

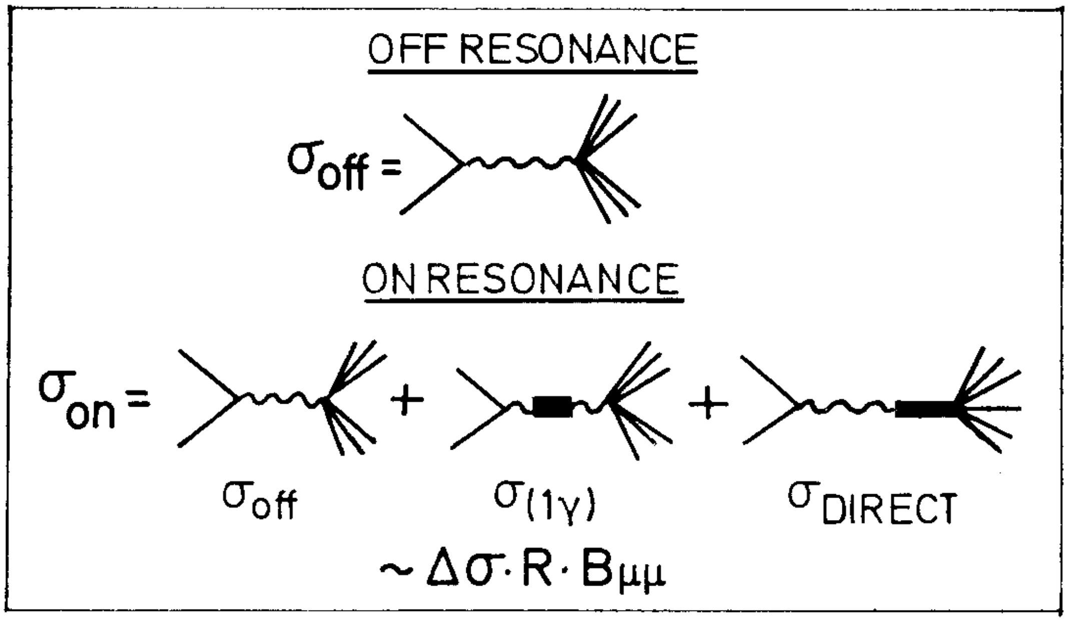

Fig. 23: Off and on resonance contributions to the annihilation cross section.

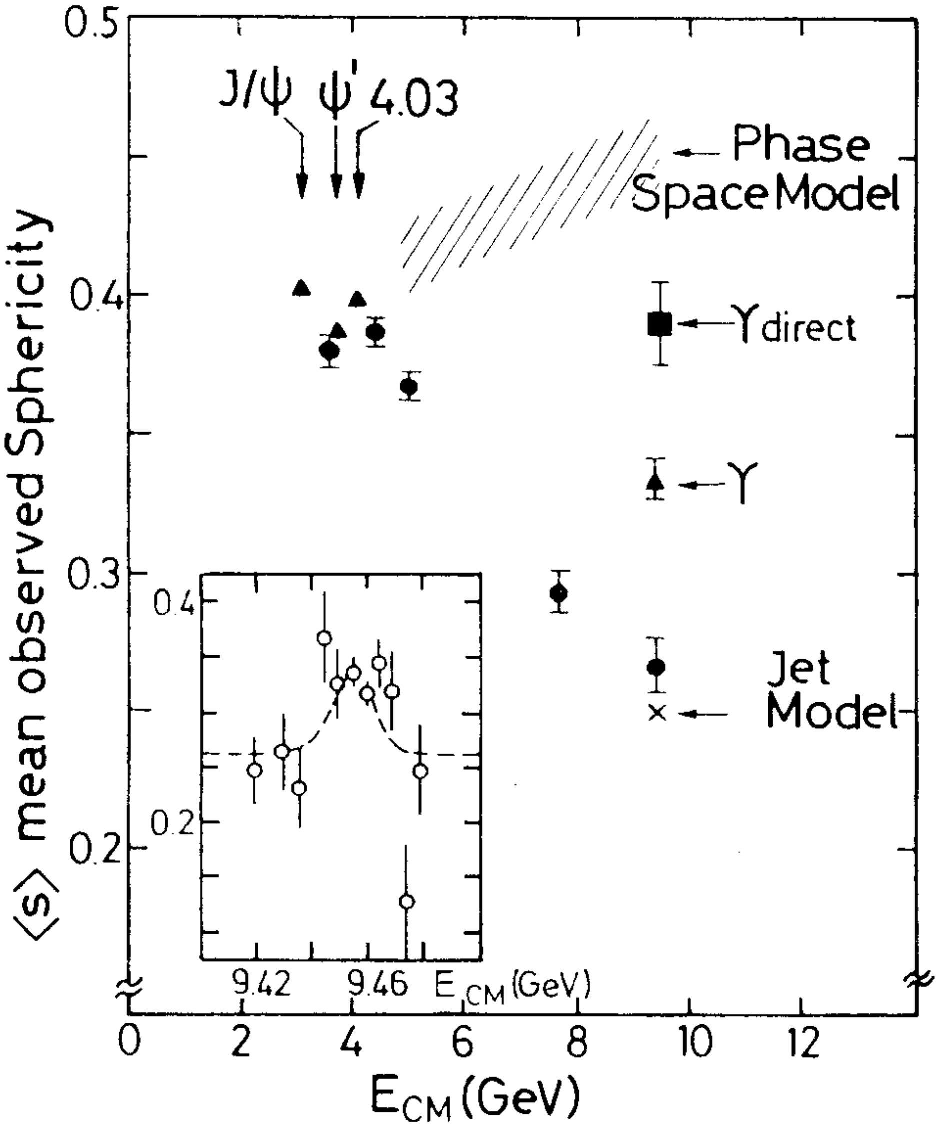

Fig. 24: PLUTO Collaboration: Observed mean sphericity of charged particles ($\geq$ 4 prongs) including the Υ region. Values without (Υ) and with (Υ direct) subtraction of nondirect terms.

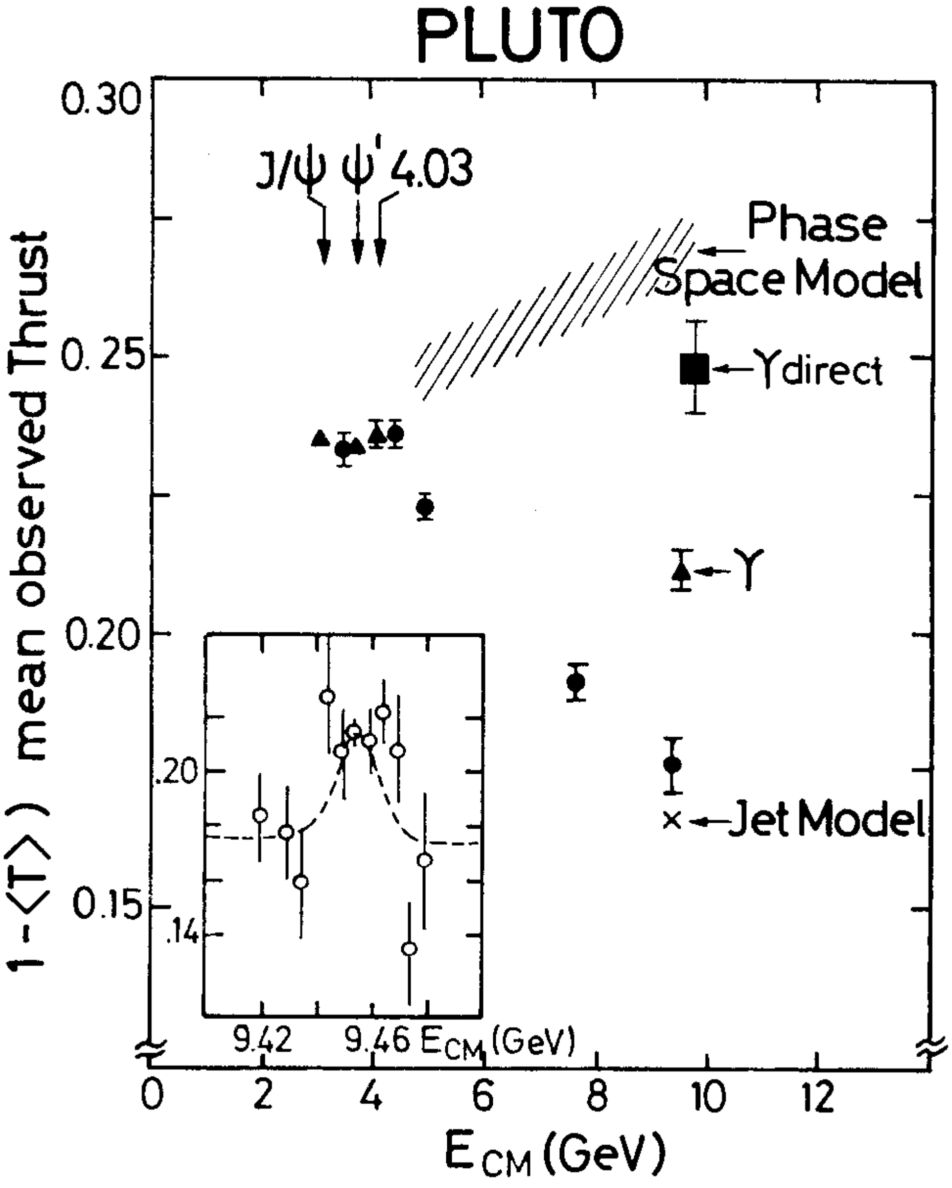

Fig. 25: PLUTO Collaboration: (1- observed mean thrust) of charged particles ($\geq$ 4 prongs) including the Υ region. Values without (Υ' and with (Υ direct) subtraction of nondirect terms.

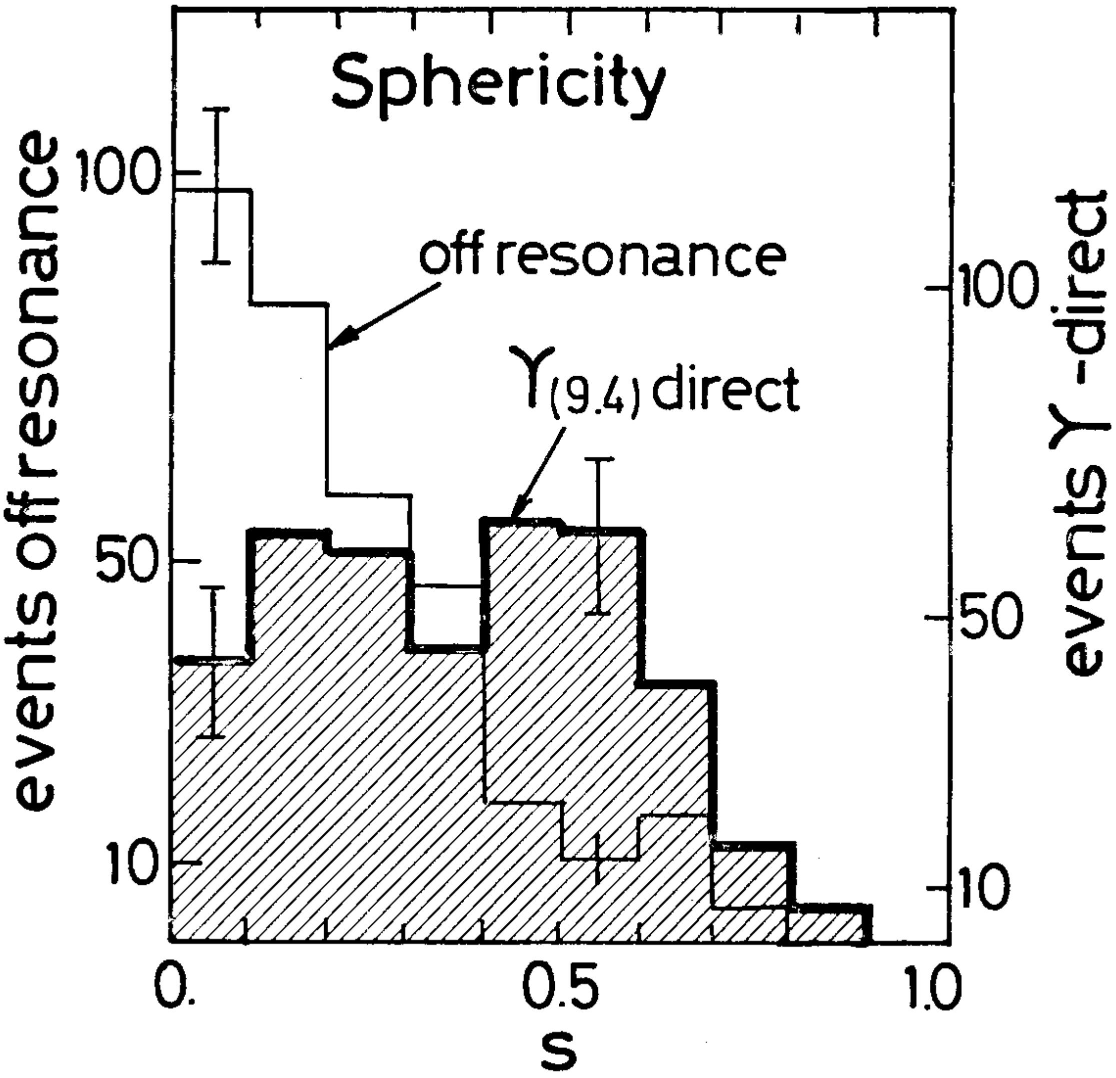

Fig. 26: DESY-Hamburg-Heidelberg-München Collaboration: Observed sphericity distribution for events on and off resonance in the Υ region. The sphericity is defined from the measured shower energies.

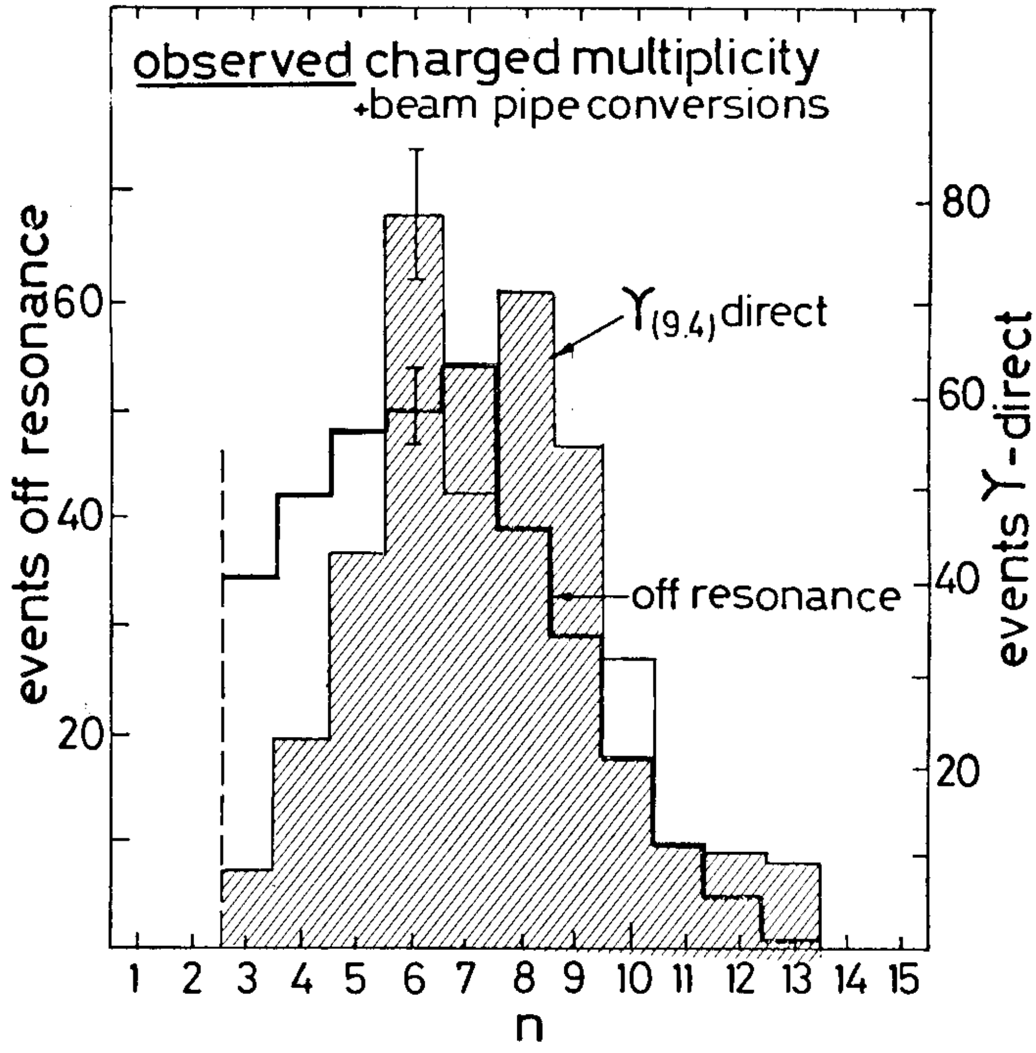

Fig. 27: DESY-Hamburg-Heidelberg-München Collaboration: Observed charged multiplicity (including beam pipe conversion) on and off resonance in the Υ region.

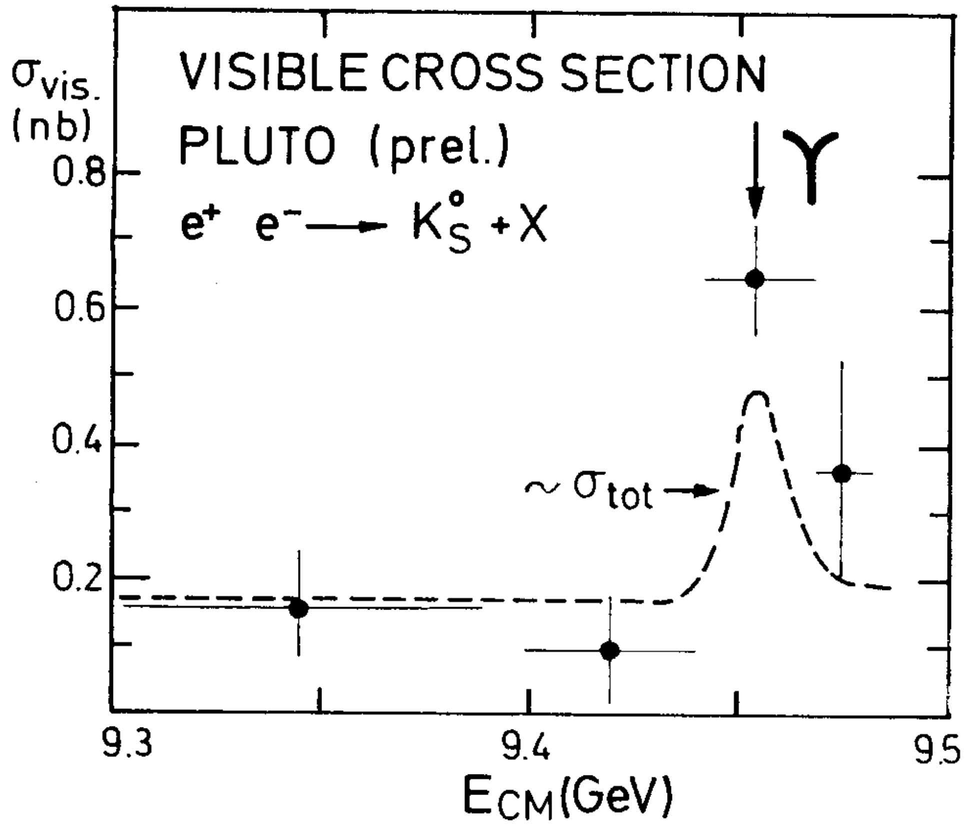

Fig. 28: PLUTO Collaboration: Visible cross section for inclusive K_S^0 production in the Υ region. The trend of the total cross section is indicated by a dashed line.

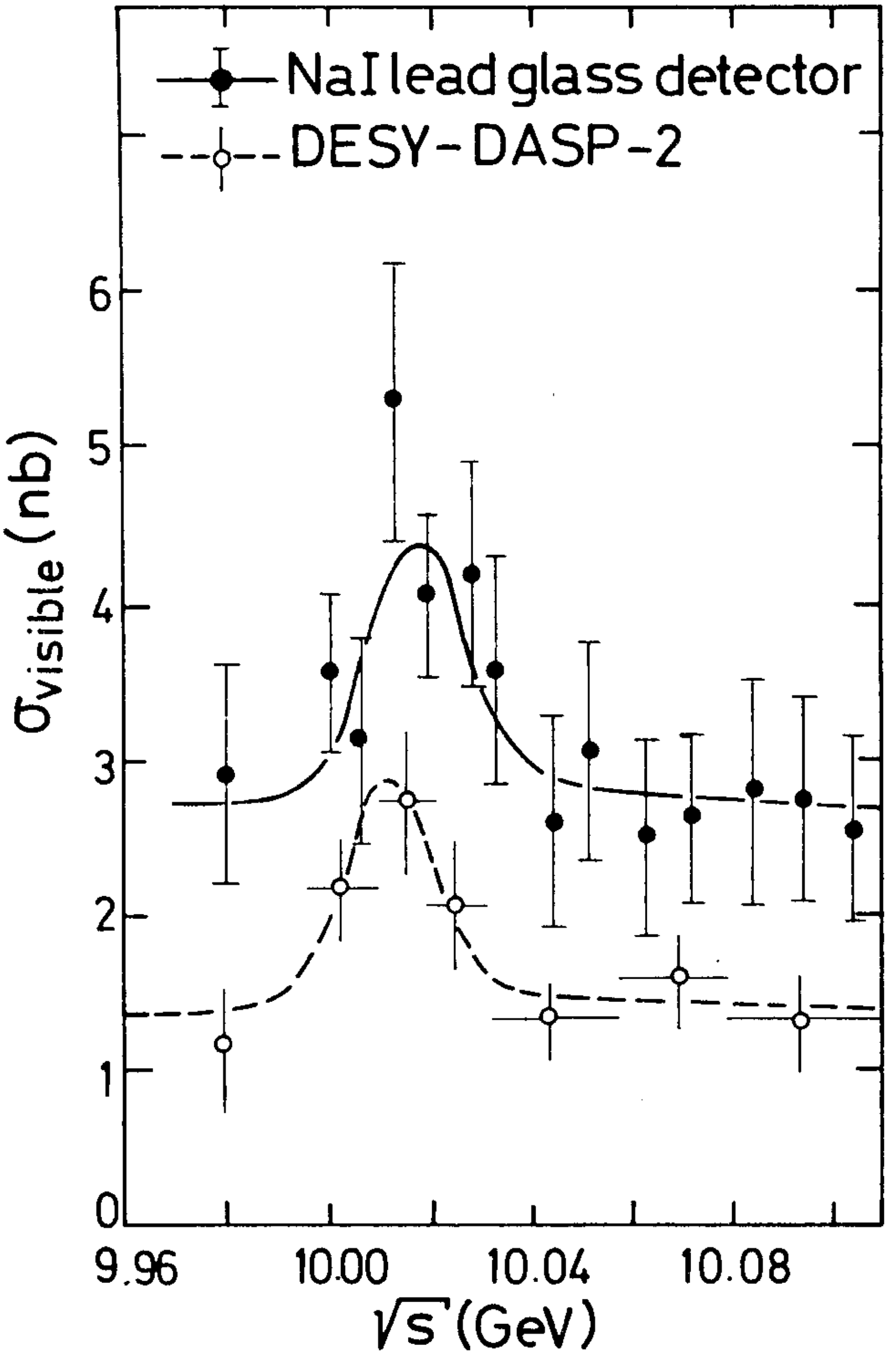

Fig. 29: DASP 2 and DESY-Hamburg-Heidelberg-München Collaborations: Evidence for the Υ' in e^+e^- annihilation.

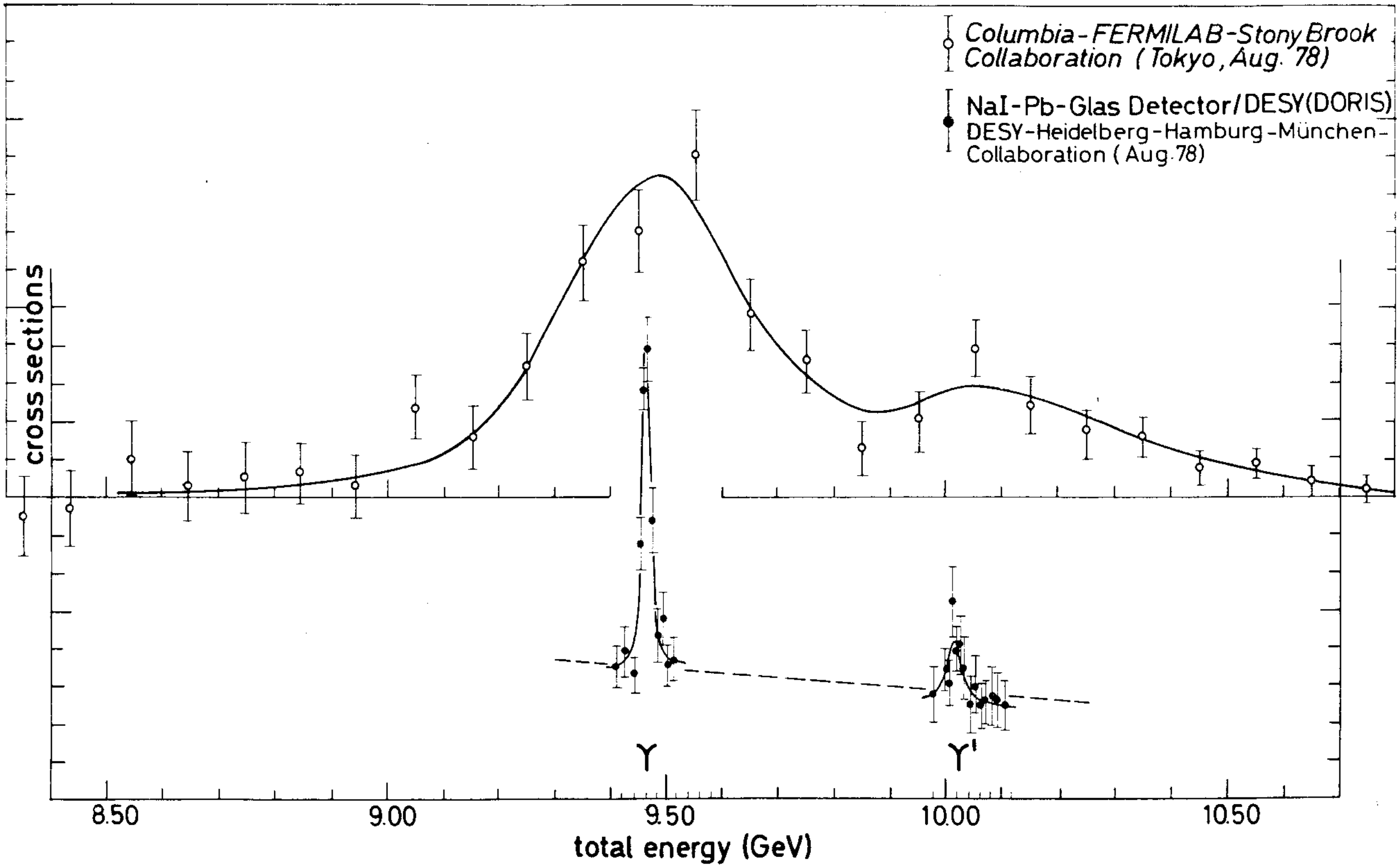

Fig. 30: Columbia-Fermilab-Stony Brook and DESY-Hamburg-Heidelberg-München Collaborations: The Υ family in hadronic and e^+e^- reactions.