A SHORT HISTORY OF e^+e^- STORAGE RINGS

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ABSTRACT :

A quick survey of the history of electron-positron colliding-beam physics is given. First, the main physical characteristics of storage rings are recalled and the kinematical and dynamical properties of e^+e^- annihilation reactions are described. Then an account is made of the most important results obtained in particle physics with e^+e^- colliding rings.

With the first generation of machines at low energies, the precise study of the vector mesons and of the form factors of pions and kaons was made. Then at intermediate energies came the astonishing result that the total cross-section was keeping much higher than previously expected. Last but not least, a new realm of physics was opened by the discovery of the new particles, of their decays to intermediate states, by the possible existence of heavy leptons and of charmed mesons.

RESUME :

On donne un aperçu rapide de l'histoire de la physique des anneaux de collisions électron-positron. D'abord, on rappelle les principales caractéristiques physiques et on décrit les propriétés cinématiques et dynamiques des réactions d'annihilation e^+-e^-. Ensuite on fait un compte-rendu des résultats les plus importants apportés en physique des particules par les anneaux de collisions e^+-e^-.

Avec la première génération de machines à basses énergies, il y eut l'étude précise des mésons vectoriels et des facteurs de forme des mésons π et k. Puis, aux énergies intermédiaires vient le résultat étonnant que la section efficace totale restait beaucoup plus grande qu'on ne s'y attendait. Enfin, le point culminant a été atteint par l'ouverture d'un champ de physique nouveau correspondant à la découverte des nouvelles particules, de leurs désintégrations en des états intermédiaires, par l'existence possible de leptons lourds et de mésons charmés.

On behalf of the organizing committee and specially of Dr. TRAN THANH VAN, I have been asked to welcome you all at this FLAINE International Meeting on Storage Ring Physics sponsored by the Centre National de la Recherche Scientifique, France.

As colliding beam physics is, at the time being, an extremely rapidly developing field, we will certainly hear, in the coming days, of new important experimental results and theoretical ideas. I dare not say that this meeting will be as exciting as the STANFORD conference, last August, but I am sure that it will be nevertheless very important for anybody engaged in this field.

It has seemed appropriate to have a short review of the e^+e^- storage rings starting from the old times of ADA to the new era opened during the last one year and half.

I shall first make a very brief comment on storage rings and on their physics motivations and properties, then we will have a short historic glance at the various past, present and future machines in the world and a parallel view on the different stages of the results of e^+e^- physics.

1. GENERALITIES ON STORAGE RINGS

Storage rings are circular accelerators where electron and positron beams are injected, accelerated and made to collide at well defined points on the rings. This has two immediate important consequences. First, since contrarily to the case of "classical" accelerators, there is no kinematical distinction between beam particles and target particles, it follows that the target particles have the same density as the beam particles (typically, there will be between 10^8 and 10^{12} particles per beam). The density of the target particles is thus much weaker than with conventional accelerators. So this must be compensated by increasing the number of times one of the beams crosses "the target" (the other beam). That can be obtained by making the beams circulate for hours in the storage rings (that is for billions of revolutions and crossings). Anyway, as the cross-sections are of an electromagnetic nature, the rate of events is low compared to what one has with conventional accelerators.

The second consequence is that, in an electron-positron collision, the center of mass system is the same as the laboratory system (this is no longer true when the beams cross at angle). There is no center of mass motion energy loss as in classical accelerators and all the energy is found again in the invariant mass of the final state. In this sense, colliding rings are more efficient than other accelerators where the energy needed is much higher than the mass of the state. In fact, this is specially true for e^+e^- rings where annihilation is possible. The possibilities of e^-e^- (or e^+e^+) devices are much fewer from this point of view. This is the reason why, although e^-e^- devices were developed historically before e^+e^- devices, they were soon given up, and nowadays 99 % of storage ring physics has come from e^+e^- collisions (this may change somewhat with the advent of two-photon physics).

2. PHYSICS MOTIVATIONS

It is useful to stress some of the main features of e^+e^- collisions. The main, fundamental characteristic is that e^+e^- systems can annihilate. Of course, some of the reactions can proceed without annihilation but most of the interest of this physics comes from the annihilation reactions. The specific characteristics of this kind of physics were stressed for the first time by CABIBBO and GATTO in 1960, 1961. Now annihilation can always, as far as we know, be interpreted through a simple diagram where one photon is exchanged between the electron and positron line and the final system f, whatever it is (Fig.1). In fact, one has to take into account radiative corrections but all the associated diagrams can be, in principle, reduced to this first diagram. Usually the complete calculations are too complicated and approximate methods have to be used. But the important feature is that the underlying physics phenomena are completely understood.

Let us consider only the case of head-on collisions :

- if $\underline{p}_+$ and $\underline{p}_-$ are quadrimomenta of the positron and electron :

$$\underline{p}_+ = (E,\vec{p}) \qquad \underline{p}_- = (E,-\vec{p})$$

the quadrimomentum $\underline{q}$ of the virtual photon is :

$$\underline{q} = \underline{p}_+ + \underline{p}_- = (2E,0)$$

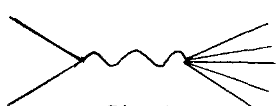

Fig. 1

One sees then that one can produce f without the intervention of strong interactions. Indeed, whereas one does not know how to compute exactly strong interaction graphs, the left-hand side half of graph 1 is exactly known and calculable. Hence one can obtain exactly the right-hand side half of graph 1 that is the interaction of a timelike photon of quadrimomentum $\underline{q} = (2E,0)$ with the state f .

A very important case occurs when f is a state of a hadron h and its antiparticle. Then, one measures directly the form factor of h, $F_h(\underline{q}^2)$ where $\underline{q}^2$ is time-like. In principle, one can in this way obtain the form factors of all the hadrons (except for the few of them which are not coupled at all to the photon, π°, η°,...) in the time-like region and perhaps of the charged leptons if they are not pointlike, that is if standard quantum electrodynamics is not valid. Let us note, for the sake of comparison, that in the spacelike region one has been able to measure the form factor of the proton in an extended range of momentum transfer, that of the neutron in a much smaller range, and that of the pion by indirect methods.

Another case of the utmost interest corresponds to the production of a single particle with the same quantum numbers as the photon. We have here a particularly clearcut process. New particles of fundamental interest have been found in this way very recently and have opened up a completely new field of particle physics. Besides, it is an especially "economical" method of production from the point of view of the incident energy since the new particle is produced at rest.

When the state f is more complicated, one still obtains very useful results by inclusive studies, or from the exclusive channel, with possibly the production of new particles or resonances associated with known particles. Besides, the study of hadronic multiparticle production has led to very unexpected and, up to now, unexplained results.

In the last ten years, colliding beam physics has developed into a very vast and rich domain of particle physics perhaps as rich as the other, earlier ones.

3. MAIN CHARACTERISTICS OF STORAGE RINGS

A storage ring is characterized by two main "figures of merit" : energy and luminosity.

E being the energy of each beam, which is well defined (of the order of a few MeV or better depending on E), kinematics allow, as we have seen, the production of objects having a mass lower or equal to 2E. Of course there are very strong restrictions on the final states produced, imposed by the conservation of various quantum numbers.

A very important parameter of a given colliding beam device is luminosity. If σ is the cross-section of a given reaction detected in a given detector, the rate of events corresponding to this reaction $\dot{n}$, at a given intersection region, is given by : $\dot{n} = L\,\sigma$ (1)

where L is a factor called luminosity depending upon the characteristics of the beams.

The luminosity is given by :

$$L = \frac{I_1 I_2}{fmS}$$

I_1 , I_2 being the current in each beam,

f being the revolution frequency,

m being the number of bunches in each beam,

S being the transverse section of the beams.

We have assumed head-on collisions.

It is obvious that it is important for a machine to have as high a luminosity as possible since the rate of events is proportional to the luminosity. Usually, the luminosity of a given machine depends strongly on the energy E , increasing with a power law between E^2 and E^4 depending on the mode of operation of the machine up to a maximum energy and then decreasing very steeply, typically as E^{-10} .

A parameter of importance for the physicist is the lifetime of the beams which determines the time available for the experiments between two injections. It depends also strongly on the characteristics of the device and is longer, the higher the energy, for a given machine.

Another interesting feature associated to the particle dynamics is that the beams of a storage ring can be transversely polarized. This phenomenon is produced by the difference of the amplitudes for radiative transition with spin flip of the electron (or positron) as a function of the orientation of the initial spin.

Starting with unpolarized beams, there is a progressive build-up of the polarization with a dependence as a function of time given by :

$$P(t) = -\frac{8}{5\sqrt{3}}\left(1 - e^{-t/\tau}\right)$$

where $\frac{8}{5\sqrt{3}} = 0.924$ is the maximum polarization of one beam reached at infinite time. The electron polarization is antiparallel and the positron polarization parallel.

In fact, the important implication is that the cross-sections of the reactions depend on the polarization of the beams through the term P_+P_- where P_+ and P_- are the polarizations of the two beams $P_+ = - P_-$.

The experimental observation of the gradual building-up of the polarization of a beam has been done on the ACO storage ring.

The influence of polarization on cross-sections has also been demonstrated at SPEAR storage ring.

It may also occur that the beams stay unpolarized at specific energies through depolarization effects.

Other features of machines are important such as, for instance, the length of the straight sections around the crossing points and the space available for large detectors.

Colliding beam devices can be made with one or two rings. In the case of two rings, one or two beams in each ring, each beam having one or several bunches. When there are two rings, it is possible to use them as e^-e^- devices. In addition, the beams can cross at an angle or undergo head-on collisions.

4. A SHORT GLANCE AT THE VARIOUS MACHINES IN THE WORLD

In a very brief review of the existing or proposed e^+e^- devices, we will not discuss the e^-e^- precursors VEPP 1 at NOVOSIBIRSK, which was an e^-e^- ring of 2 x 160 MeV and the 2 x 550 MeV e^-e^- PRINCETON-STANFORD storage ring.

The possibility of e^+e^- collisions in storage rings was experimentally demonstrated for the first time in 1964 with ADA by a FRASCATI-ORSAY collaboration, at ORSAY.

Since, then, we can classify the e^+e^- devices in two categories :

1°) The "low energy machines"

ACO at ORSAY, which was the first strong focusing storage ring, VEPP 2 and VEPP 2-M, at NOVOSIBIRSK. These machines covered (and still cover) the region of the 3 first vector mesons ρ, ω, ϕ, VEPP 2-M reaching a total energy of 1400 MeV.

2°) The "high energy machines"

The first in operation was ADONE, at FRASCATI, which is also the lowest energy one of this category. The CEA device was a "by-pass" on an electronsynchrotron. The two other operating ones, SPEAR at STANFORD (sometimes with the distinction between the 2 chronological stages of operation SPEAR 1 and SPEAR 2) and DORIS, at HAMBURG, go much higher in energy than the mass of the two objects ψ and ψ'. DCI at ORSAY will not go much higher than the ψ' but hopefully with a large luminosity. VEPP 3 has a higher energy and should begin operating soon.

3°) The "very high energy" projects

There are essentially two projects, PETRA, at HAMBURG, with a total energy of 38 GeV and PEP at STANFORD with a total energy of 30 GeV.

It is also planned in a more or less remote future, to add to each of these devices an extra ring for protons which would provide e-p collisions. The energy of the protons would range from 80-100 GeV with classical magnets and to 200 GeV with superconducting magnets.

In table 1 are given the principal characteristics of the existing or planned e^+e^- rings. The present luminosity is given singly when the ring has already been operating for a certain length of time. Otherwise the nominal luminosity is also given.

Fig.2 shows a curve of luminosity, as a function of energy for both the operating rings and some planned ones.

5. LOW-ENERGY PHYSICS RESULTS

After the very first results from ADA which proved that there were indeed e^+e^- annihilations in colliding rings, a new domain of physics was opened at NOVOSIBIRSK and ORSAY by observation of annihilations in the 1 GeV total energy range.

First, it was realized that the cross-sections were higher than usually predicted, thanks to the existence of the 3 vector mesons ρ, ω, ϕ which were copiously produced. Indeed, it provided the best tool to study precisely the properties of these vector mesons. The interference ρ-ω was observed and precisely measured at ORSAY, as well as the ω-ϕ interference. The form factors of the π and K mesons in the time like region were determined with a good accuracy and various other decay modes, both charged and radiative, were studied.

TABLE 1

Main characteristics of the colliding beam devices

	Ring	Structure	Maximum total energy GeV	Maximum observed luminosity $cm^{-2}\ s^{-1}$	Maximum design luminosity $cm^{-2}\ s^{-1}$
No longer in operation	VEPP 2 Novosibirsk	one ring	1.4	3×10^{28}	
	CEA Cambridge	Synchrotron + by pass	5.	2×10^{28}	
Operating	ACO Orsay	one ring	1.1	10^{29}	
	VEPP 2-M Novosibirsk	one ring	1.5	7×10^{28} (1974)	10^{30}
	ADONE Frascati	one ring	3.1	7×10^{29}	
	SPEAR Stanford	one ring	8.4	1×10^{31} at 2E = 6 GeV	10^{32}
	DORIS Hamburg	two rings	8	10^{30} at 2E = 4 GeV	3×10^{32}
Under construction	DCI Orsay	two rings 4 beams	3.7		10^{32}
	VEPP 3 Novosibirsk	one ring	6.		10^{30}
	VEPP 4 Novosibirsk	one ring	14.		10^{31}
Proposed	PEP		30.		10^{32}
	PETRA		38.		10^{32}

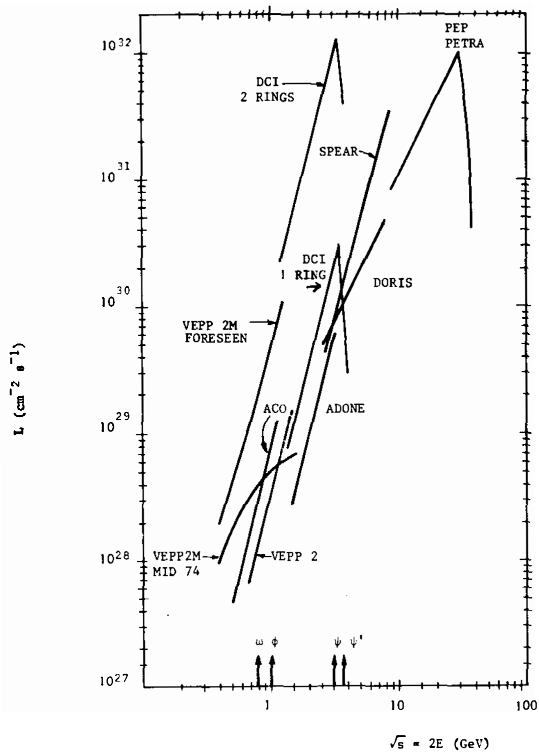

Fig.2 :
Luminosities as a function of energy for e^+e^- colliding rings. For operating rings, the maximum observed luminosity is given. For rings under construction, the design luminosity is given.

On the theoretical side, the interpretation of low energy phenomena by the vector dominance model (VDM) was very successful. Some other problems such as sum rules caused a considerable amount of interest which decreased afterwards when it was realized that the existence of higher vector mesons could very well complicate the interpretation of the sum rules.

In addition, the e^+e^- initial state provides specially good conditions to study Q.E.D. The validity was established with improved cut-offs through the reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \gamma\gamma$.

Later, these reactions were studied at higher energies, providing extremely accurate checks of the validity of Q.E.D. which correspond to upper limits on the distance for which Q.E.D. is valid of some 10^{-15} cms.

6. INTERMEDIATE ENERGIES

ADONE at FRASCATI, CEA at HARVARD, and SPEAR at SLAC, opened up the range of total energies between 1.5 and 3 GeV although the energies at CEA and principally SPEAR were pushed much higher.

Various exclusive reactions were examined at these energies and indications of new vector mesons possibly a $\rho'(1250)$ and most likely a $\rho''(1600)$ were obtained. The large number of channels open in this energy range and the smallness of the individual cross-sections make these experiments difficult.

It was believed that the total hadronic cross-section decreased rather rapidly. In a free quark field model for instance, it would drop like $1/s$, the cross-section being :

$$\sigma(e^+e^- \to \text{hadrons}) = \frac{4\pi\alpha^2}{3s} \sum_i Q_i^2$$

where Q_i is the charge of the i^{th} parton of spin 1/2.

Usually, one gives the ratio :

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$\sigma(e^+e^- \to \mu^+\mu^-)$ having a very well established $1/s$ behaviour.

Here, one just has :

$$R = \Sigma\, Q_i^2$$

In fact it is found that R is relatively large even at the lowest energies in the intermediate regions and that it increases with energy.

It was at ADONE that the large values of the hadronic cross-section were put in evidence for the first time, and this was found to be a very important discovery of storage rings and very challenging for the theorists.

7. HIGH ENERGIES

SPEAR and DORIS have run up to total energies of $\sim$ 8 GeV but the great news came in november 1974 from the range 3-4 GeV with the discovery of two extremely narrow new particles $\psi(3095)$ and $\psi'(3684)$. This was a shock since, owing to their very small width, any classical explanation such as daughters of known vector mesons had to be rejected.

Figs 3, 4 and 5 show the production of the ψ and ψ' through the reactions $e^+e^- \to$ hadrons, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to e^+e^-$.

This opened such an exciting domain of physics that some people call it "new physics" as opposed to the "old physics", the domain of energy below the new particles. This is perhaps a little unfair because of the slightly deprecatory appreciation on a physics which gave important results and prepared the way to the new field.

Soon after, the main leptonic and hadronic decay modes of the particles were determined. The ψ and ψ' were established as objects of an hadronic nature with the quantum numbers of the photon, an isospin 0 and a G-parity -1. The ψ' decays about 60 % of the time in ψ + something else.

Besides, amongst the decays of the ψ and ψ', new states were found. The ψ shows a decay $\psi \to \underset{\hookrightarrow \gamma\gamma}{X} + \gamma$ where two of the gamma-rays cluster around a mass of 2.8 GeV (Fig.6). This was discovered at DORIS.

The ψ' shows cascade decays to states sometimes called P_C, through reactions :

$$\begin{array}{l} \psi' \to \gamma + P_C \\ \qquad\qquad \hookrightarrow \gamma + \psi \end{array} \qquad \text{(fig.7)}$$

or

$$\begin{array}{l} \psi \to \gamma + \chi \\ \qquad\qquad \hookrightarrow \text{hadrons} \end{array}$$

The χ and P_C have energies at 3530, 3510, 3410 MeV with some

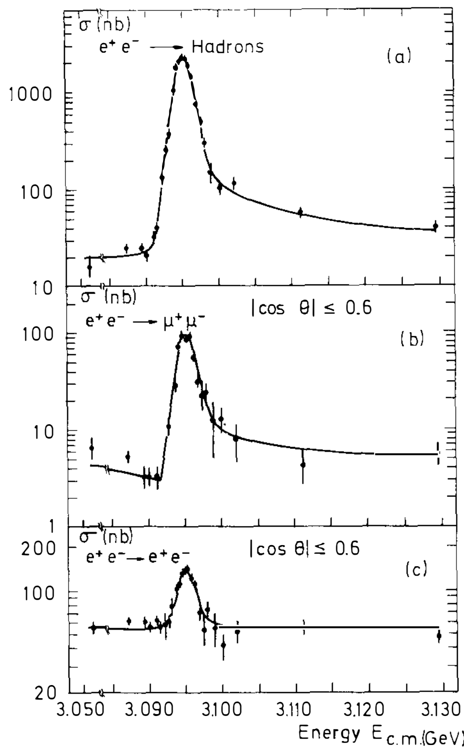

FIG.3 : CROSS-SECTIONS FOR
a) $\psi \rightarrow$ HADRONS b) $\psi \rightarrow \mu^+\mu^-$ c) $\psi \rightarrow e^+e^-$
(SLAC-LPL COLLABORATION)

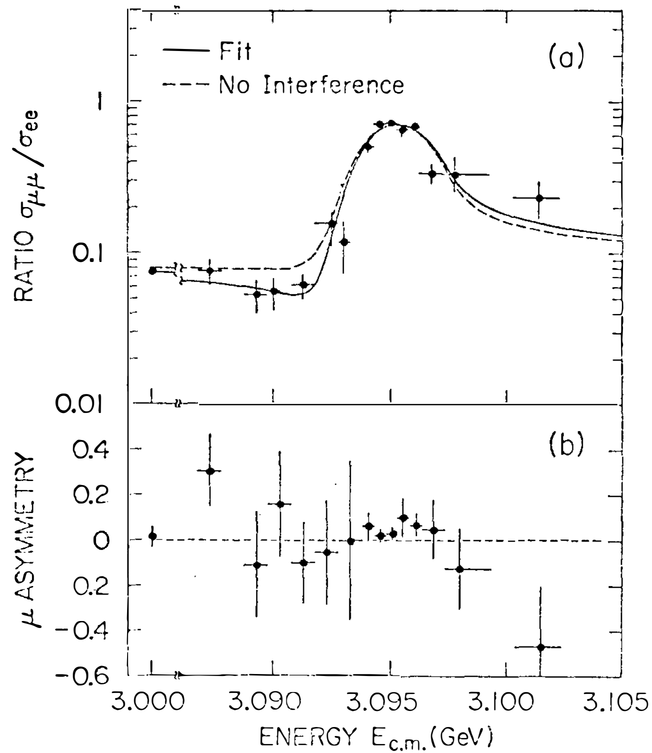

FIG.4 : a) INTERFERENCE EFFECT IN $\psi \rightarrow \mu^+\mu^-$ CROSS-SECTION. THE DATA ARE PRESENTED AS $\sigma_{\mu\mu}/\sigma_{ee}$ VS. 2E.
b) FRONT-BACK ASYMMETRY IN $\psi \rightarrow \mu^+\mu^-$ PRODUCTION
SLAC-LBL COLLABORATION.

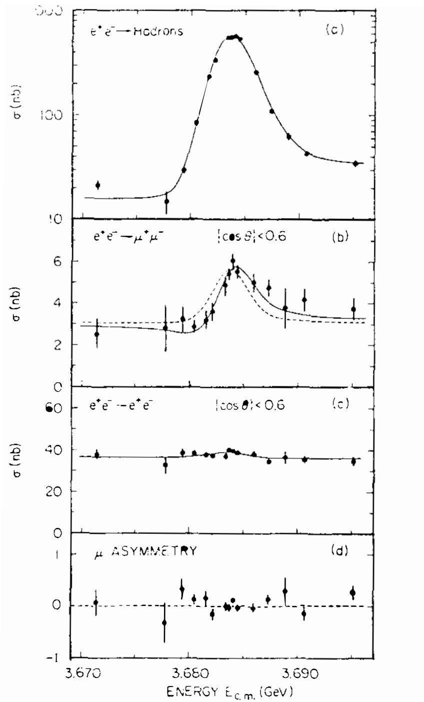

FIG.5 : ψ' CROSS-SECTIONS VERSUS $E_{CM} = 2E$
a) $\psi' \to$ HADRONS
b) $\psi' \to \mu^+\mu^-$
c) $\psi' \to e^+e^-$
d) FRONT-BACK ASYMMETRY IN $\psi' \to \mu^+\mu^-$
SLAC-LBL COLLABORATION

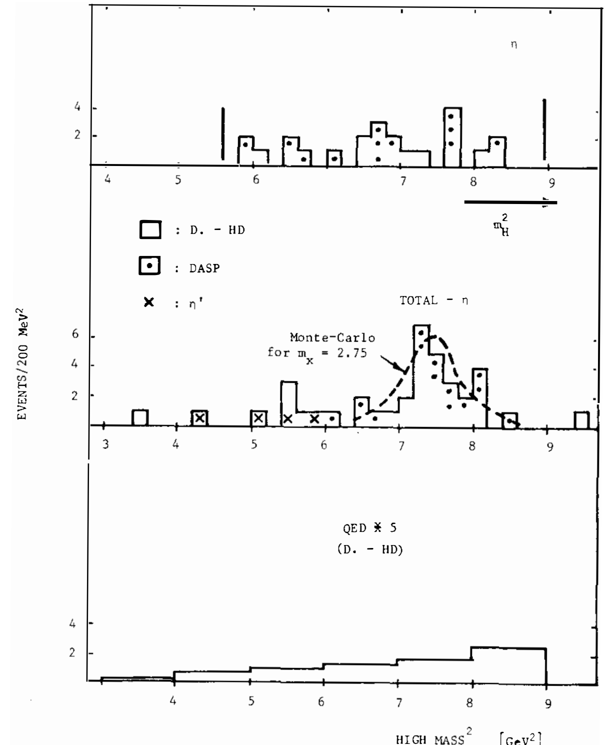

FIG.6 : HIGH MASS SQUARE SPECTRUM OF THE DASP + DESY-HEIDELBERG RESULTS
a) EVENTS WITHIN THE η BAND
b) EVENTS OUTSIDE THE η BAND
c) QED EVENTS (TIMES 5).

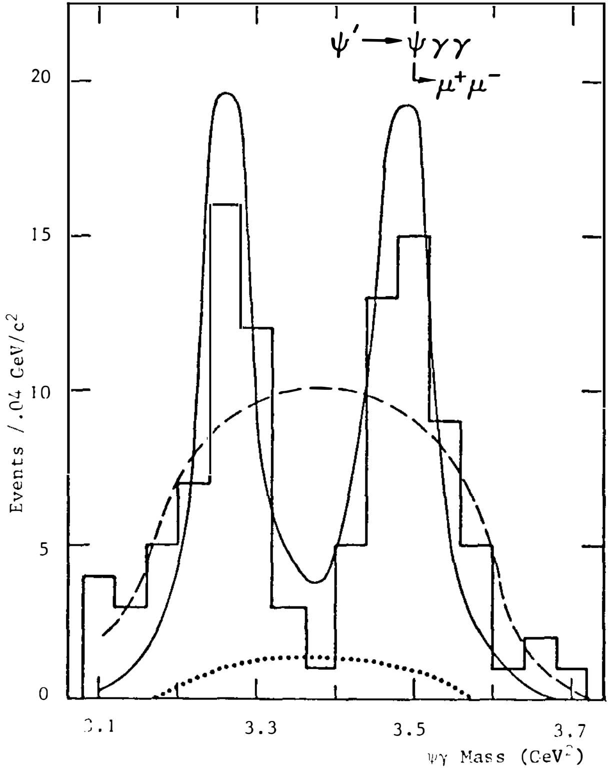

FIG.7 : RECONSTRUCTED MASS OF THE P_C INTERMEDIATE STATE.
SLAC-LBL RESULTS.

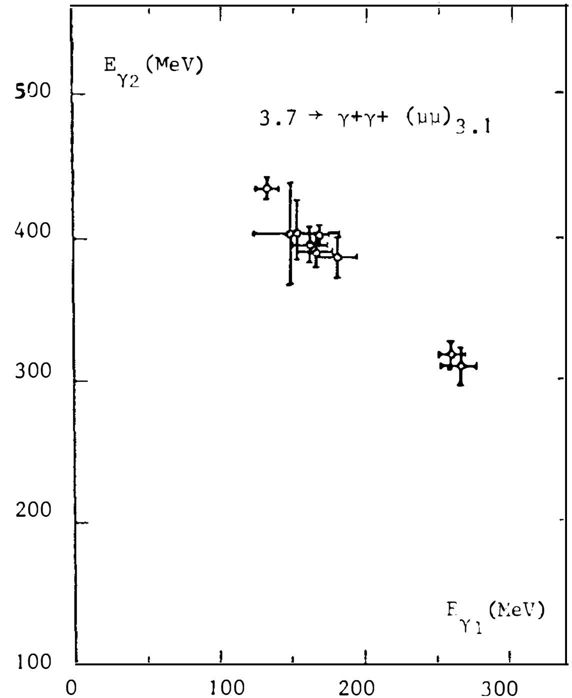

FIG.8 : SCATTER PLOT OF THE TWO PHOTON ENERGIES FOR CANDIDATES FOR THE DECAY $\psi' \to \gamma\gamma\,\psi$, $\psi \to \mu^+\mu^-$
DASP RESULTS.

energy ambiguity for the cascade decays (Fig.8). The question whether χ and P_C are the same states is still unsolved.

This is the starting point of a new spectroscopy. Nowadays the preferred model for the theoreticians is the charm model with the new "charmed" quark c and then the SU(4) symmetry, (although the color models have still strong supporters). In a charmonium picture of the new particles, one derives level schemes where the X(2800) could be the η_C paracharmonium state $1\ ^1S_o$, the ψ and ψ' being the orthocharmonium 1 and 2 $^3S_1$. Some of the χ and P_C could be the 1 ^3P states (Fig.9).

Unfortunately, an extensive search at SLAC has failed to reveal the production of charms (charmed mesons or charmed baryons). There is also quite a complicated structure between 3.9 and 4.4 GeV with perhaps some new resonances ψ'', ψ''' ... (Fig.10) which should be studied and which perhaps decay to other states of the spectroscopy.

Other interesting results in this energy range concern the inclusive hadronic cross-sections where scaling indeed shows up for large x.

But perhaps the most exciting fact besides the new particles, is the relatively abundant production of pairs $e^{\pm}\mu^{+}$ of opposite charges. Besides, the cross-section of the process as a function of energy seems to show a threshold effect (Fig.11). So it is possible that one observes the decays of charmed spin 1 mesons. It is possible also that one has to deal with leptonic or semi-leptonic decays of heavy leptons. The momentum distribution seems to favour slightly this latter hypothesis (Fig.12).

8. CONCLUSION

It is perhaps time to give a short list of the problems which remain to be solved. Some of them, may be, have already found an answer in the last weeks or months, and we will hear of them during the next talks.

At low energies, the rare decay modes especially radiative, would give useful information on the various quark models.

At intermediate energies, the $\rho'(1250)$ and $\rho''(1600)$ should be disentangled in the $4\pi^{\pm}$ and $2\pi^{\pm}2\pi^{o}$ modes, as well as in the $\pi^+\pi^-$ mode. The values for multihadron cross-sections should be determined in a reliable way. One should also look for the analogue states ω', ϕ', ω'', ϕ'' ...

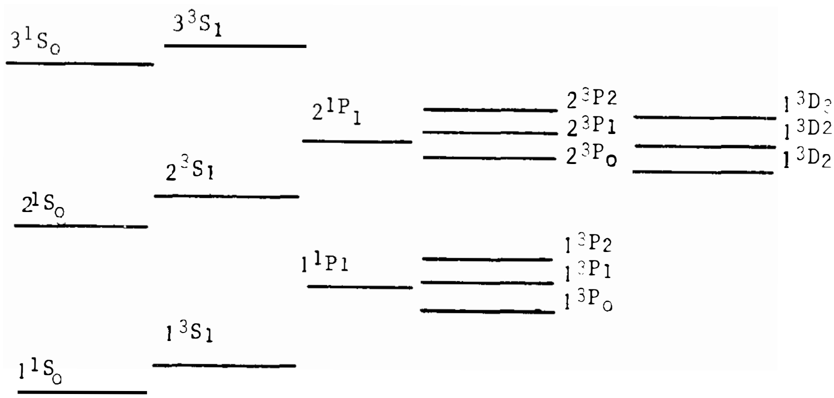

FIG.9 : THE FERMION-ANTI-FERMION SPECTROSCOPY.

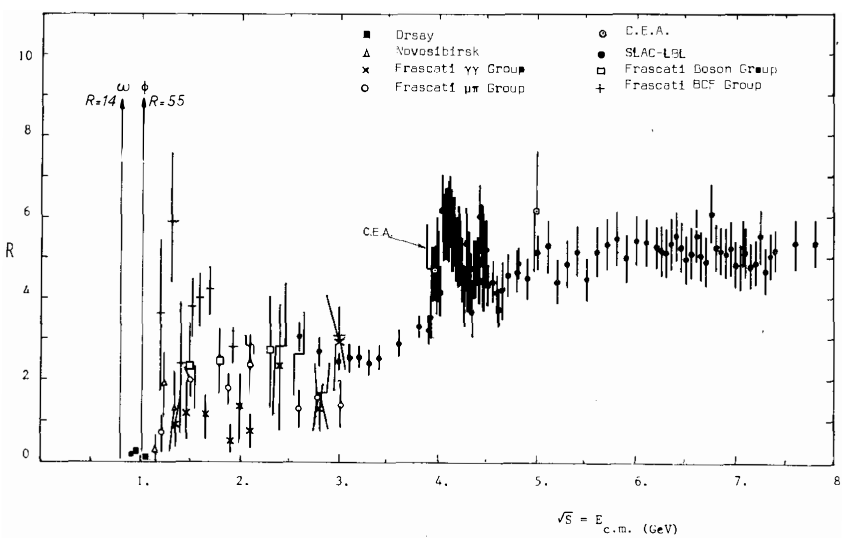

FIG.10 : THE RATIO R VERSUS $W = \sqrt{s} = 2E$ BETWEEN 0 AND 8 GEV.
THE $e^+e^- \rightarrow \pi^+\pi^-$ REACTION RESULTS HAVE NOT BEEN TAKEN INTO ACCOUNT.

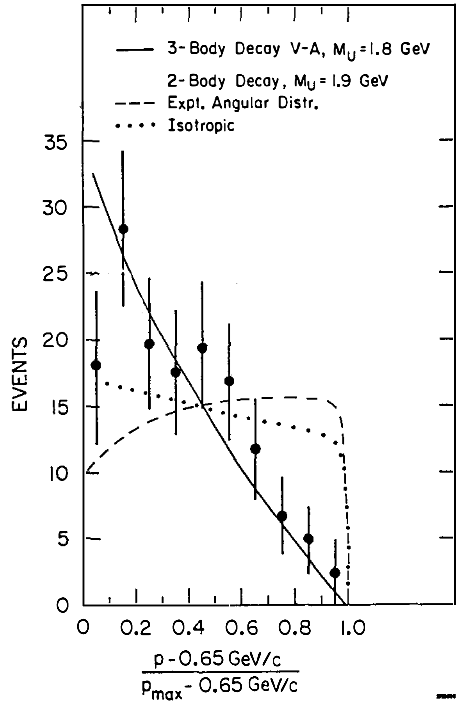

FIG.12 : THE DISTRIBUTION IN [illegible] = $(p - 0.65)/(p_{MAX} - 0.65)$ FOR ALL E_{CM}.
THE SOLID CURVE REPRESENTS THE EXPECTED DISTRIBUTION FOR THE DECAY OF HEAVY LEPTONS OF MASS 1.8 GeV/c^2.
THE DOTTED CURVE REPRESENTS TWO-BODY ISOTROPIC DECAY OF A BOSON OF MASS 1.9 GeV/c^2.
THE DASHED CURVE SI THE SAME AS THE DOTTED CURVE EXCEPT THAT THE DISTRIBUTION IN COLLINEARITY ANGLE HAS BEEN SET TO FIT THE DATA.

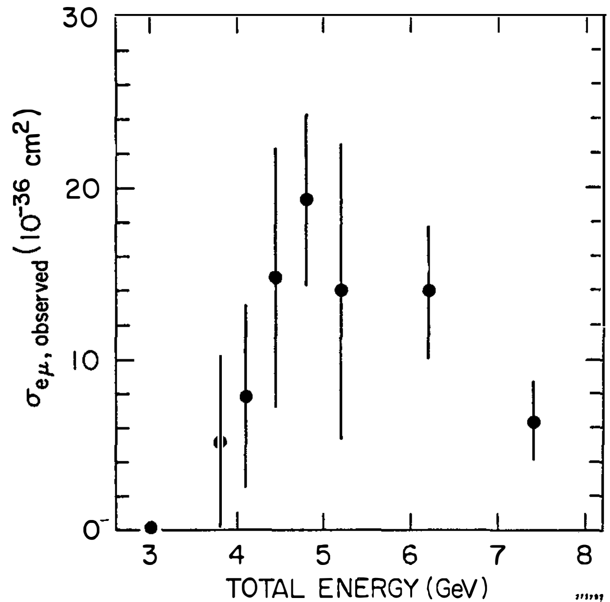

FIG.11 : THE CROSS-SECTION FOR OBSERVING AN e AND A μ AND NO OTHER PARTICLE AS A FUNCTION OF E_{CM}. THESE DATA HAVE NOT BEEN CORRECTED FOR MOMENTUM AND ANGLE CUTS AND FOR THE GEOMETRY OF THE DETECTOR.

At high energies, there are a lot of problems :

1. The structure between 4.0 and 4.4 GeV should be resolved.

2. Are there higher resonances for instance at 6 GeV ?

3. What is the higher energy behaviour of R ?

4. Precise study of the X(2800) ?

5. How many levels are there between ψ' and ψ ?
   What are their quantum numbers and decays ?

6. Are there heavy leptons at a mass around 2 GeV ?
   If not, where do the $e\mu$ pairs come from ?

7. What are the 30-40 % missing decays of the ψ' ?

8. Why are charmed objects not found in storage rings ?

9. What about the charged to neutral ratio ?

10. For theoreticians, charm or color ? (and also quark confinement, asymptotia ...).

This list is, of course, not exhaustive. For an answer to many of these questions we are looking forward to PETRA and PEP and the "New new physics".