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e^+e^- COLLIDING BEAM EXPERIMENTS

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e^+e^- COLLIDING BEAM EXPERIMENTS

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The aim of these lectures is to discuss the present experimental situation of the e^+e^- colliding beam physics. As everybody knows, this rather young field of activity in elementary particle physics is in rather fast developing situation and more data at higher energies will be hopefully available in the near future.

In these lectures experimental details will in general be omitted to the extent they are not essential to discuss and understand the physical results. A somewhat greater emphasis has been given to the most recent data coming from ACO, Adone and CEA, since a rather exhaustive literature is available for the previous researches |1|.

The history of e^+e^- colliding beam machines begins in the sixties and has already reached its full maturity period in terms of energy and luminosity (see Table 1).

It is maybe worth recalling that the luminosity L represents the storage rings counterpart of the intensity for a conventional accelerator. Namely, an e^+e^- induced reaction whose cross section is σ, in a set-up whose detection efficiency for this reaction is ε, gives a counting rate

$$\dot{N} = L\varepsilon\sigma$$

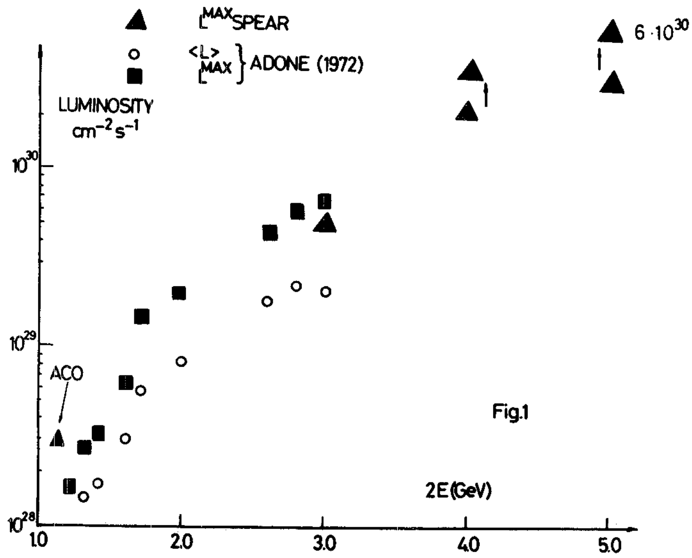


Fig.1

Table 1.
e^+e^- storage rings

Machine	Maximum total c.m. energy (GeV)	Radius (m)	L ($cm^{-2}s^{-1}$)	Status
Ada Frascati Italy	0.5	0.64	$2\cdot10^{25}$	Active from 1961 to 1965
Vepp-2 Novosibirsk USSR	1.4	1.6	$3\cdot10^{28}$ (1 GeV)	1966
ACO Orsay France	1.1	3.4	$3\cdot10^{28}$ (1 GeV)	1967 → (1975)
ADONE Frascati Italy	3.0	16	$7\cdot10^{29}$ (3 GeV)	1970 →
CEA BY-PASS Cambridge USA	5.0	27	$4\cdot10^{28}$ (4 GeV)	1971 → 1973
SPEAR Stanford USA	5.5 (→9)	34	$6\cdot10^{30}$ ($\rightarrow10^{32}$)	1973 →
DORIS Hamburg W.G.	7	46	10^{32}	First injection January 1974
DCI Orsay France	3.6	$\sim$15	10^{32}	Ready to go on 1975

The presently available luminosities ($\sim10^{30}$) correspond to circulating currents of the order of 50 mA, which means $\sim10^{11}$ circulating $e^{\pm}$ with a transverse cross sectional area of a few mm^2. The luminosity performances of some of the storage rings now in operation, are shown in Fig. 1.

By using e^+e^- storage rings a great amount of experimental information has been achieved so far, and it is the aim of these lectures to summarize and comment on the available experimental data (at least the more recent ones) and give some ideas on what is expected in the future.

As far as the present experimental situation is concerned, the most relevant topics to be covered are listed in Table 2.

Table 2

e^+e^- storage rings. Recent experimental results on:

1. Q.E.D. tests
$$\begin{cases} e^+e^- \to e^+e^- \\ e^+e^- \to \mu^+\mu^- \\ e^+e^- \to \gamma\gamma \end{cases}$$
$$\begin{cases} e^+e^- \to e^+e^-\gamma \\ e^+e^- \to e^+e^-e^+e^- \\ \qquad\quad\;\; e^+e^-\mu^+\mu^- \end{cases}$$

2. Heavy lepton search
$e^+e^- \to$ H.L. + $\overline{\text{H.L.}}$

3. Electromagnetic form factors (π, K, p) in the time-like region

4. Many hadron production in e^+e^- annihilation processes

I. Q.E.D. TESTS

This is a subject which has been deeply considered in the past and here I will summarize the most important results as far as the first lower-order reactions $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to \gamma\gamma$ are concerned. This means that only typical results will be presented with no attempt to have a complete description of the abundant amount of work already performed. Also, experimental details will be omitted |1,2|.

As far as the second order (2 photons in the lowest order) processes are concerned, a slightly more diffused description will be given essentially due to their more recent exploitation in experiments at e^+e^- storage rings.

Ia. Elastic e^+e^- (Bhabha) scattering $e^+e^- \to e^+e^-$

Several experiments have been performed on the $e^+e^- \to e^+e^-$

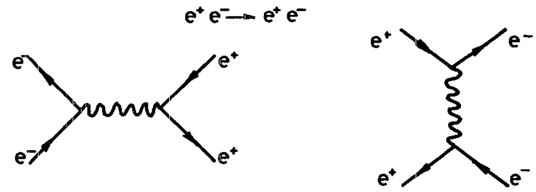


Fig. 2

$q^2 = -s^2 \sin^2 \frac{\theta}{2}$ $q^2 = s^2$

(+ Radiative corrections)

Experiments agree with theory within accuracies of:

$\pm 4\%$ up to $\sqrt{s} = 3$ GeV (Adone) } for the absolute values
$\pm 8\%$ up to $\sqrt{s} = 5$ GeV (CEA) } of the cross section

$\pm 2\%$ up to $\sqrt{s} = 5$ GeV } as far as the angular distributions are concerned

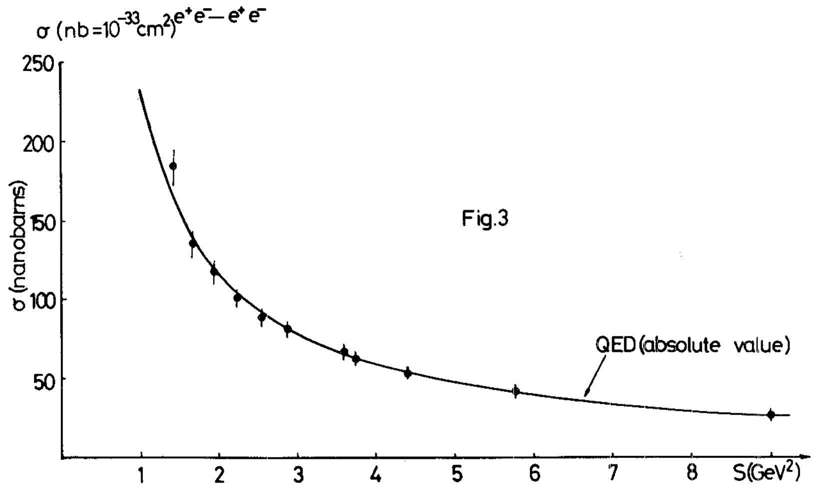
reaction with rather accurate results up to the total c.m. energies of 5 GeV. These results have been compared with the values predicted according to Q.E.D. when radiative corrections have been properly taken into account. (See Fig. 2).

Some results from the most recent measurements are shown in Figs. 3 and 4, together with the expected Q.E.D. predictions (absolute values of the cross sections and angular distributions). The agreement is very good so that one can safely state that the experimental results for the $e^+e^- \to e^+e^-$ reaction are the ones one could expect according to Q.E.D. within an accuracy of 4% up to $\sqrt{s} = 3$ GeV and 8% up to $\sqrt{s} = 5$ GeV (as far as the absolute values are concerned).

Ib. Muon production $e^+e^- \to \mu^+\mu^-$

This process proceeds via a single annihilation graph with only a time-like photon involved (see Fig. 5).

Measurements of this process have been performed at ACO, Novosibirsk, Adone and CEA and the results of the comparison with theory are shown in Fig. 6. The agreement between the experiments and the theory is good within $\pm 10\%$.



Monitor: small angle Bhabha scattering (low q^2 space-like process where Q.E.D. is expected to be valid): $<q^2>_{Monitor}$ = = $2\cdot10^{-3}$ GeV^2. Adone - BCF (M. Bernardini et al. |9|).

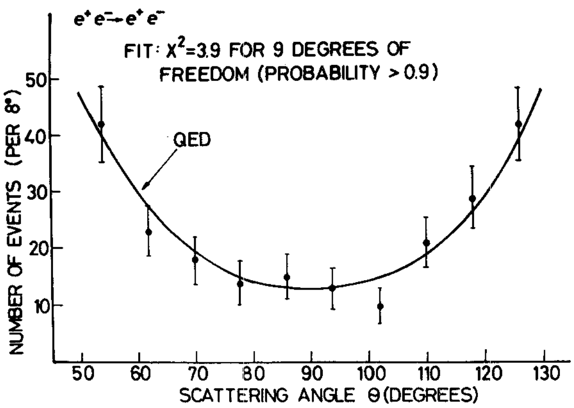


Fig.4

Angular distribution for $e^+e^- \rightarrow e^+e^-$ at 5 GeV (CEA - BY PASS, H. Newmann et al. 1973 Bonn Conference). Absolute values: $\frac{\sigma_{exp}}{\sigma_{th}(QED)}$ = 1.03 ± 0.08. Fit: x^2= 3.9 for 9 degrees of freedom (probability >0.9).

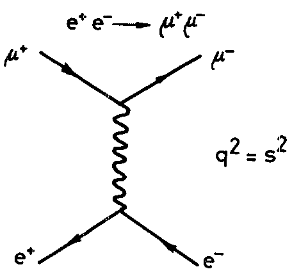


Fig.5

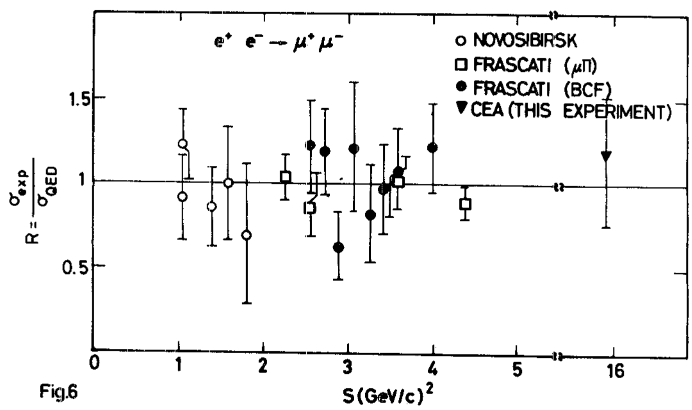


Fig.6

Ic. Two-photon e^+e^- annihilation

The third reaction that has been studied is the annihilation process $e^+e^- \rightarrow \gamma\gamma$. It proceeds via virtual electron states and so tests the electron propagator (see Fig. 7).

A sketch of the results of measurements performed at Orsay, Novosibirsk, Frascati and CEA is shown in Fig. 8, where good agreement clearly appears with the Q.E.D. predictions (both in absolute values and angular distributions $\sim\pm 15\%$).

Id. Two-photon collision processes

Besides the above-mentioned reactions, Q.E.D. also controls processes in which two virtual photons are exchanged at the lowest order and their collision is the source of final states such as lep-

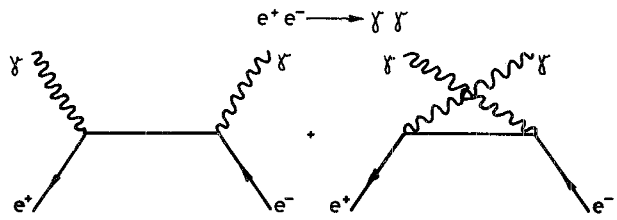


Fig. 7

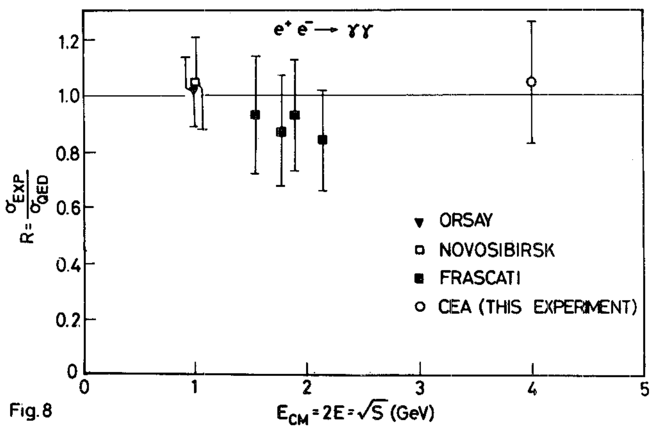
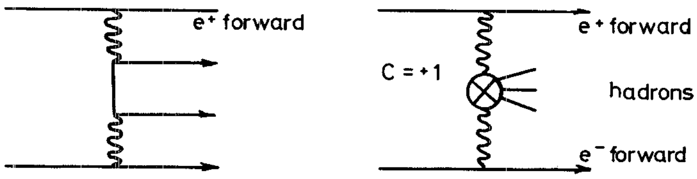


Fig. 8

ton pairs or hadronic system with C = +1.

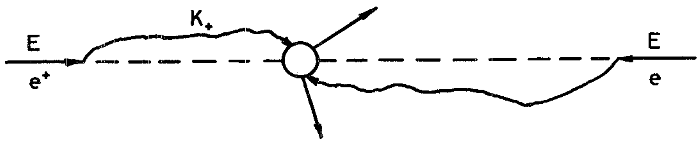
These processes are described by simple diagrams, as shown in Fig. 9. Now, in spite of the fact that the cross section for two-photon exchange processes is depressed by a factor α^2 with respect to the usual one-photon annihilation graphs, due to the higher probability that low-energy virtual photons have to be emitted, it happens that the cross sections for these two-photon processes increase logarithmically with energy. So, since the one-photon channels decrease with increasing energy, these two-photon processes very soon become predominant. Calculations |3| performed in the frame of the equivalent photon approximation (E.P.A.) show that the energy dependence of two-photon cross sections is of the type $\propto (\ln \frac{E}{m_e})^2$ (see Fig. 10).

Fig. 9 Two – photon processes



Both the incoming e^+ and e^- irradiate a photon. The two quasi-real photons interact and materialize into a system.

Fig. 10 The energy behaviour of two-photon processes



E.P.A.: Both the incident $e^{\pm}$ are replaced by uncorrelated equivalent photon spectra:

$$\frac{\alpha}{\pi}\,\frac{E^2+(E-K)^2}{E^2}\,\ln\left(\frac{E}{m_e}\right)\cdot\frac{dK}{K}$$

$$\sigma(e^+e^- \to e^+e^-) \propto \frac{\alpha^4}{\pi}\,\left(\ln\frac{E}{m_e}\right)^2 \;\ldots\ldots ,$$

where E is the energy of each beam and K the energy of the virtual emitted photon.

A more quantitative evaluation of the importance of this kind of processes as compared with the one-photon ones is shown in Fig. 11 (taken from ref. |3|).

Two-photon mechanism processes have been recently experimentally investigated at Adone up to total c.m. energies of 3 GeV by two groups (the so-called $\gamma\gamma$ and $\mu\pi$ groups). A first measurement which showed the $e^+e^- \to e^+e^-e^+e^-$ reaction was performed in Novosibirsk |4|.

I will now present some recent results concerning collisions

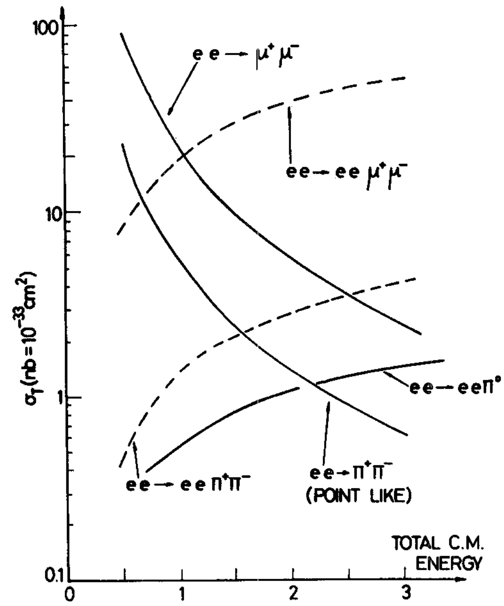


Fig. 11

between two photons in the processes:

$$e^+e^- \to e^+e^- \; e^+e^-$$
$$\to e^+e^- \; \mu^+\mu^-$$
$$\to e^+e^- \; \pi^+\pi^-$$

as detected by Adone. Some experimental details will be given in this case, since they help to understand what has been measured. A sketch of the experimental set-ups is given in Figs. 12-13. A tagging system has been installed inside the bending magnets of Adone adjacent to the straight section in order to detect the forward going $e^{\pm}$ and measure their energy.

The main properties of the tagging system are shown in the following table:

Tagging system		$x = \frac{P}{E} = \frac{\text{forward } e^{\pm} \text{ momentum}}{\text{beam momentum}}$
Momentum acceptance	$0.1 \le x \le 0.8$	curved counters
	$0.75 \le x \le 0.9$	small
Momentum resolution	$\frac{\Delta P}{P} = \pm 4\%$ at $x = 0.7$	
Angular acceptance	$\Delta\theta_{vert.} = \pm 8$ mrad	
Geometrical efficiency	$\sim 50\%$	

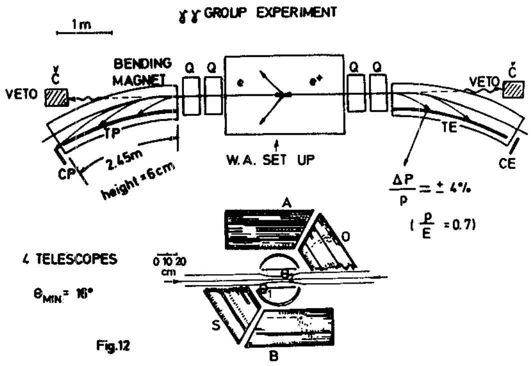


Fig.12

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-e^+e^-$$
$$\to e^+e^-\mu^+\mu^-$$

γγ group experiment

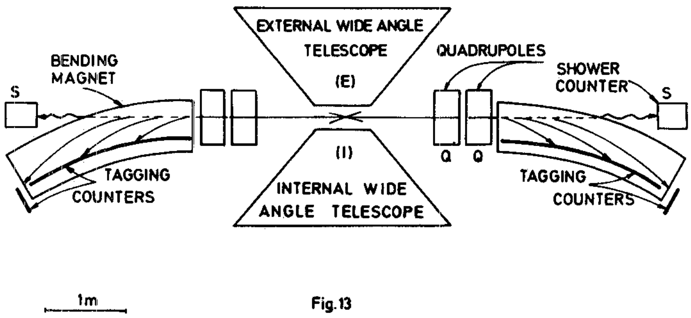


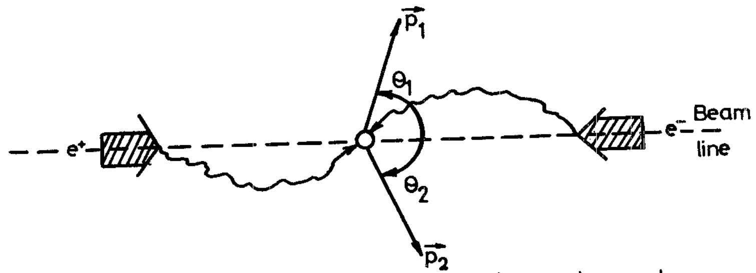
Fig.13

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-e^+e^- \; . \; \theta_{min} = 45^o.$$
$$\mu^+\mu^-$$

μπ group: F. Ceradini, M. Conversi, S. D´Angelo, L. Paoluzi, R. Santonico, R. Visentin (+ G. Barbiellini, M. Ferrer, S. Orito, T. Tsum for the 2γ interaction part).

Two-photon interaction events have been detected with these setups. Their kinematics is described by the following quantities (see the following table).

Kinematics



1,2: wide-angle emitted particles (e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$) coplanar with the beams ($|\Delta\phi|<10^o$)
Wide angle particles c.m. velocity $\equiv \beta$

$$\beta = \frac{(K_+ - K_-)}{K_+ + K_-} = \frac{\sin(\theta_1 + \theta_2)}{\sin\theta_1 + \sin\theta_2}$$

The recorded events under different final state topologies are shown in Fig. 14.

The agreement with the equivalent photon approximation calculations is rather good, as can be seen in Fig. 14 and Fig. 15 ($\gamma\gamma$ group results).

As far as the $e^+e^- \to e^+e^-\mu^+\mu^-$ is concerned, the situation is summarized in Fig. 16. The agreement with the expected values according to E.P.A. is good as can also be seen in Fig. 17a,b.

The conclusion for these two photon reactions is that such processes have been detected with the presently existing storage rings. Therefore, with the high energy and high luminosity machines it becomes evident that there is a possibility of studying C = +1 hadronic states as well as $J^P = 1^-$ states accessible via the usual one-photon mechanism. Furthermore, e-μ and e-π scattering can (in principle at least) be investigated through the virtual photon mechanism.

Another reaction in the realm of the Q.E.D. that has been investigated at Adone (C. Bacci |7|) is the wide angle electron-positron bremsstrahlung $e^+e^- \to e^+e^-\gamma$ at total c.m. energies of 1.4-3.0 GeV (see Fig. 18). The results show good agreement with Q.E.D. predic-

$e^+e^- \to e^+e^-\ e^+e^-$ Analyzed events: 122

(forward: e_F^+, e_F^-) (wide angles: e_W^+, e_W^-)

Detected + Recognized	Measured quantities	Analysis
e_W^+, e_W^-, $e_F^\pm$	θ_1, θ_2, 44 events (168 nb^{-1})	Calculate $\beta = \beta(\theta_1,\theta_2)$+compare with E.P.A. expected distribution |5|. ($\gamma\gamma$ group) (see Fig. 15)
e_W^+, e_W^-, e_F^+, e_F^-	θ_1, θ_2, K_+, K_- 12 events (290 nb^{-1})	- Check the relationship $\beta = \frac{(K_+-K_-)}{K_++K_-} = \frac{\sin(\theta_1+\theta_2)}{\sin\theta_1+\sin\theta_2}$ (O.K) - compare with theory |6| (11.6±1.1) events expect. ($\mu\pi$ group) (O.K.)
e_W^+, e_W^-, $e_F^\pm$	θ_1, θ_2, $K_\pm$ 64 events (290 nb^{-1})	- calculate K_x of the photon from the nondetected forward e^x and find: 43 ev from Q.R.P. 9 ev from V.P. 12 ev ambiguous ($\mu\pi$ group)

Fig. 14

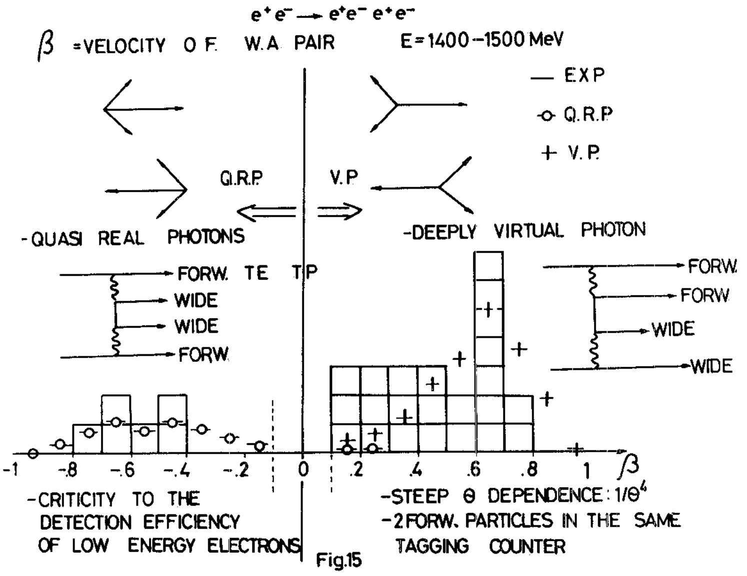


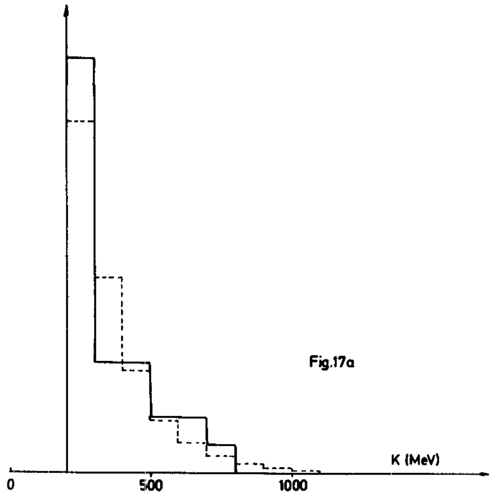
Fig.15

$e^+e^- \to e^+e^- \mu^+\mu^-$ Total events: 34

($\mu\pi$ group) |6|

Detected Recognized	Measured Quantities	Analysis
$\mu_W^+, \mu_W^-, e_F^+, e_F^-$	θ_1, θ_2 K_+, K_- p_1, p_2 (by range) 10 events (290 nb^{-1}) (+4 events $\theta_{1,2}, K_\pm$)	- Reconstruct $K_\pm^{rec}$ from $\theta_{1,2}$ $p_{1,2}$ + compare with $K_\pm^{meas}$ as measured by tagging: $\Rightarrow |\Delta K| = |K^{rec} - K^{meas}| \simeq 0$ (see Fig. 17) - K distributions with E.P.A. O.K. (Fig. 17) - total number expected according to E.P.A. = 11 O.K.
$\mu_W^+, \mu_W^-, e_F^\pm$	$\theta_1, \theta_2, K_\pm,$ p_1, p_2 56 ev.tot. 20 (ΔK=0) 36 (bkgr.)	- compare with the expected number: 28 ev.expected $\sim$ O.K.

Fig. 16



Photon momentum distribution relative to $e^+e^- \to e^+e^-\mu^+\mu^-$ events. Dotted histogram is based on E.P.A. calculations.

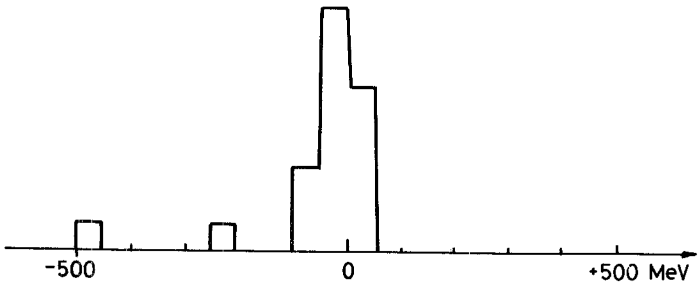


Fig. 17b

$\Delta K = (K^{rec} - K^{meas})$ distribution for 10 events (DT-μ). These data are due to Adone-$\mu\pi$ group.

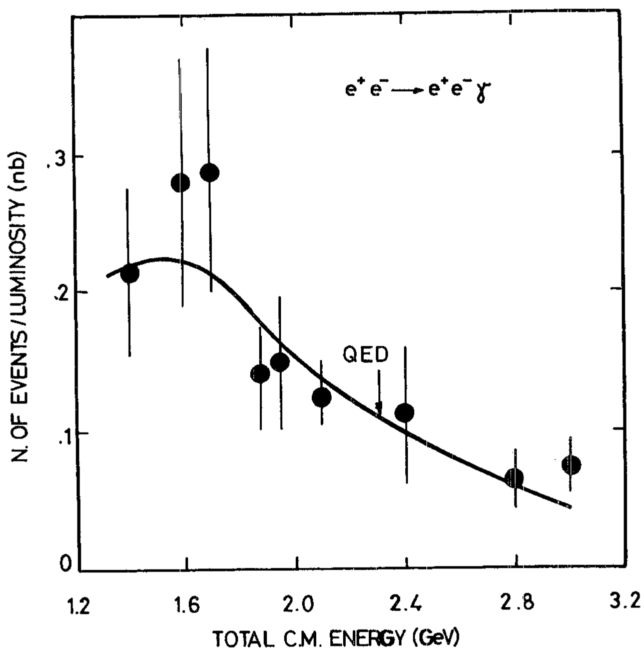


Fig.18

The invariant mass of the system $(e^{\pm},\gamma)$ has been calculated (2 values for each event) and compared with Q.E.D. predictions in order to look for possible heavy excited electrons: $e^{*} \rightarrow e + \gamma$. These data are due to the $\gamma\gamma$ group (Adone). There are 118 events.

tions. An analysis of the same data looking for a limit to the existence of a heavy excited electron e^{*} (F. Low [7]) produced in the $e^{+}e^{-} \rightarrow e^{\pm}e^{*\mp}$ reaction (based on the invariant $(e^{\pm},\gamma)$ mass distribu-
$\quad\quad\quad\quad\quad\quad\quad \hookrightarrow e^{\mp}\gamma$
tion) has given an upper limit on λ (the $ee^{*}\gamma$ coupling constant) in the e^{*} mass range from 0.6 to 2.2 GeV (see Fig. 19).

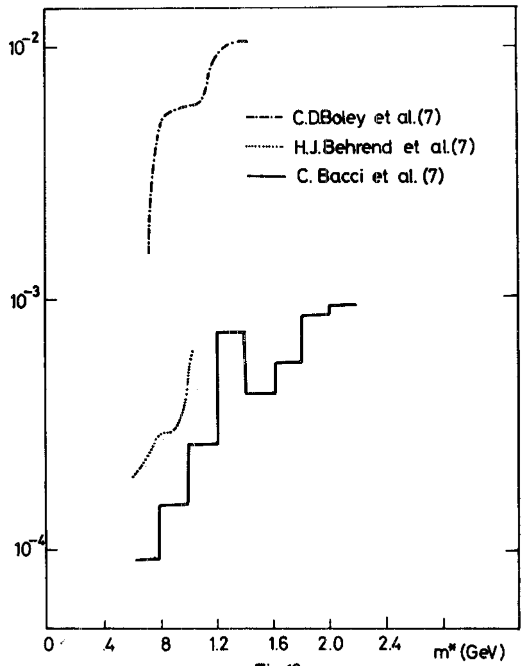


Fig.19

Upper limits of λ^2. λ^2 represents $ee^*\gamma$ coupling constant and m^* mass of the heavy electron. $\sigma(e^+e^- \to$ $\to e^{\pm}e^{*\mp}$ $)$ is calculated ($e^{*} \to e^{\pm}\gamma$) from the Hamiltonian $H_I = (\frac{e\lambda}{m^*})\ \overline{\Psi}_{e^*}\sigma_{\mu\nu}\Psi_e F^{\mu\nu}_{+} +$ h.c.

II. HEAVY LEPTON SEARCH IN e^+e^- EXPERIMENTS

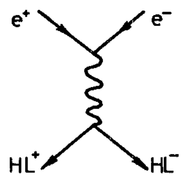
Besides the above mentioned heavy excited electron, other kinds of heavy leptons might be produced in e^+e^- induced reactions. Namely, via the one time-like photon channel any type of heavy lepton can be produced (see Fig. 20).

The cleanest way to look for these leptons in e^+e^- experiments is to look for their possible decay modes in which μ's and electrons are involved. In fact, hadronic channels could be heavily contaminated by other competing reactions. Let us consider the reaction channels (see |9|)

$$
\begin{array}{lcl}
e^+e^- \to HL^+ & + & HL^- \\
\quad\quad\ \Downarrow & & \ \Downarrow \\
\quad\quad e^+\nu\nu & & e^-\nu\nu \\
\quad\quad \mu^+\nu\nu & & \mu^-\nu\nu \\
\quad\quad \nu\text{+hadrons} & & \nu\text{+hadrons}\ ,
\end{array}
$$

where ν means a generical neutrino or antineutrino whatever its nature (ν_μ, ν_e, ν_{HL} if any, $\overline{\nu}_\mu$, $\overline{\nu}_e$, etc.) is. The quoted group Bolo-

Fig. 20. Heavy leptons
$e^+e^- \to HL + \overline{HL}$



If heavy leptons are Dirac point particles:

$$\sigma(e^+e^- \to HL + \overline{HL}) = \frac{\pi\alpha^2}{2E^2}\,\beta(1 - \frac{\beta^2}{3})$$

(E energy of each $e^{\pm}$ beam, β velocity of H.L.)

For E >> M_{HL}, $\beta \to 1$

$$\sigma \to \sigma(e^+e^- \to \mu^+\mu^-) \approx \frac{2\times 10^{-32}}{E^2}\ \mathrm{cm}^2$$

(See Review article by Perl |8|).

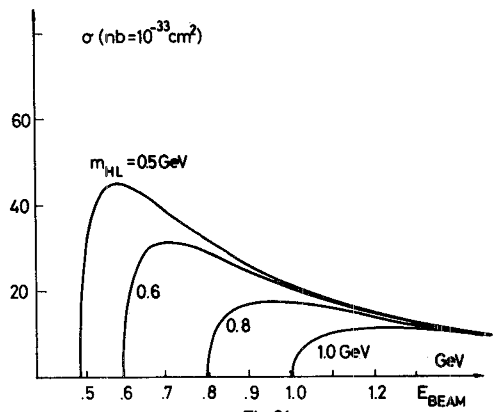


Fig.21

Calculated heavy lepton production cross section versus colliding beam energy for different m_{HL} (search for anomalous threshold-like effects in any channel).

gna-CERN-Frascati collaboration looked for mixed leptonic modes ($\mu^\pm e^\mp$), where non-collinear and non-coplanar (with respect to the beam axis) e-like and μ-like tracks in the spark chambers of the set-up should appear (see Fig. 21). They find no good event in a total integrated luminosity of $\sim$450 nb^{-1}.

Furthermore, the energy dependence of the reactions

$$e^+e^- \rightarrow 2 \text{ leptons} + \text{anything}$$
$$\rightarrow \text{lepton} + \text{hadron} + \text{anything}$$

was inspected looking for anomalous threshold-like effects since the production cross section as a function of energy, is expected |10| to show peculiar patterns when the available energy is such as to produce a heavy lepton.

In order to put a limit to the production rate of possible heavy leptons, the decay rates for the leptonic and hadronic modes must be estimated. If one assumes pure leptonic modes (heavy lepton coupled only to ordinary leptons) the first-order weak interaction theory gives $\Gamma(HL \rightarrow \nu_{HL} + \mu + \nu_\mu) \approx \Gamma(HL \rightarrow \nu_{HL} + e + \nu_e)$ with typical life-times of the order of 10^{-11} sec in the mass region of 1 GeV and a lower limit for the mass of the heavy lepton is found to be:

$$m_{HL} \geq 1.45 \text{ GeV} \quad (95\% \text{ confidence level}).$$

In the case of hadronic decay modes (that is if the heavy lepton is coupled to both ordinary leptons and hadrons) the estimate of the relative weights of the various decay modes is less direct and assumptions have to be made on the coupling heavy lepton-hadron. (Various estimates give as a reasonable |11| proportion 1:1:1 for the $\mu\nu\nu$, $e\nu\nu$ and $\geq$2 hadron modes, respectively). In this case a limit to the mass of the heavy lepton can be found, that is

$$m_{HL} \geq 1 \text{ GeV} \quad (95\% \text{ confidence level}).$$

So much as far as the present experimental situation is concerned. It is clear, however, that more energetic e^+e^- machines that will become available in the future, will constitute one of the best tools for investigating the existence of heavy leptons. Among the main advantages of this technique are the relatively large production cross section and the threshold-like energy behaviour which makes it possible to obtain clear excitation curves.

III. ELECTROMAGNETIC STRUCTURE OF HADRONS. TIME-LIKE FORM FACTORS.

e^+e^- storage ring annihilation experiments of the kind

$$e^+e^- \rightarrow B\,\bar{B}\ ,$$

where B, $\bar{B}$ is any couple hadron-antihadron, provide a suitable experimental tool for measuring the hadron electromagnetic form factors in the time-like region,whereas lepton elastic-scattering experiments give the space-like part of these form factors.

In fact, it is known that, under general hypotheses, the amplitudes for pair production in e^+e^- collisions and lepton elastic scattering can be expressed in terms of a few form factors, analytic functions of the variable q^2, the square of the four momentum transfer.

Analogous connections hold between inelastic scattering processes in the space-like region of the momentum transfer and many-hadron production processes in e^+e^- annihilation (time-like).

In the following, the situation of the $e^+e^- \rightarrow B\bar{B}$ measurements will be discussed.

Mesons time-like form factors

The space-like region is explored by electroproduction experiments. As far as the time-like part of this form factor is concerned its connection with the cross sections for the reactions (one photon approximation):

$$e^+e^- \rightarrow \pi^+\pi^-$$

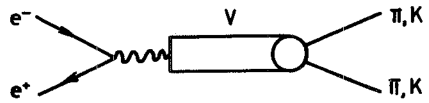
$$e^+e^- \rightarrow K^+K^-$$

is given by the relation

$$\frac{d\sigma}{d\Omega} = \frac{\pi\alpha^2}{4}\,\frac{\beta^3_{\pi,K}}{q^2}\,|F_{\pi,K}(q^2)|^2 \sin^2\theta\ ,$$

$$\sigma = \left(\frac{\pi\alpha^2}{3}\right)\frac{\beta^3_{\pi,K}}{q^2}\,|F_{\pi,K}(q^2)|^2\ .$$

For low values of q^2 (lower than 1.1 $(GeV/c)^2$) the governing process is the production of unstable vector mesons ρ, ω, ϕ according to the well-known mechanism |12|



It is worth noticing that the assumed one-photon mechanism for the process imposes the value $\ell=1$ for the angular momentum of the final state. In the case of the pion, the $\pi^+\pi^-$ system has to be in an I=1 state, so that the $F_\pi(q^2)$ form factor is really connected with the coupling of isovector photons with hadrons. This is not true in the case of the kaon form factor which is also related to the isoscalar photon coupling.

The vector meson role in the meson-antimeson e^+e^- annihilation processes shows up very clearly in the region $q^2 \leq 1$ (GeV/c)^2, where bumps in the cross sections have been found just at the vector meson masses. An extensive series of measurements has been performed at ACO and Novosibirsk |12|, and the main results are summarized in Fig. 22. The dashed line is the best fit to ACO points using a Gounaris-Sakurai formula in which the ω contribution ($\omega\to 2\pi$) is taken into account. The parameters entering into the fit:

$$m_\rho = (775 \pm 7)\mathrm{MeV},\ \Gamma_\rho = (149 \pm 23)\mathrm{MeV},$$

$$\frac{\Gamma(\rho\to e^+e^-)}{\Gamma_\rho} = (4.0\pm 0.5)\ 10^{-5},\ \left|\frac{\Gamma(\omega\to\pi\pi)}{\Gamma(\omega)}\right|^{1/2} = 0.2\pm 0.05$$

$$\text{Phase} \quad f_{\omega\pi\pi}/f_{\rho\pi\pi} = (87.5\pm 15.4)^\circ .$$

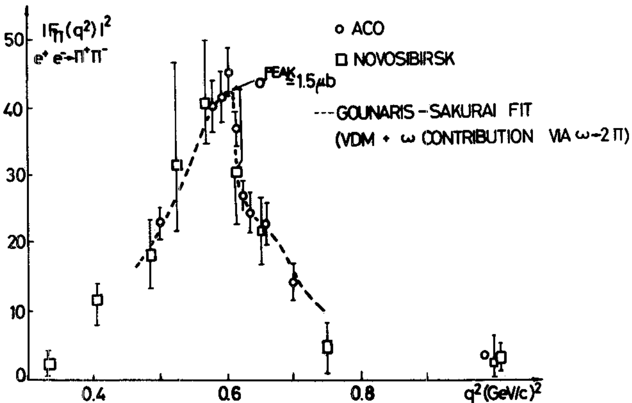


Fig.22

Electromagnetic form factor for mesons as measured at ACO and Novosibirsk |12|.

As far as the kaon is concerned it turns out that at energies around the ϕ mass, the kaon (K^+) form factor $|F_K|^2$ is governed by the mechanism

$$e^+e^- \to \phi \to K^+K^- .$$

The main results of experiments performed at ACO and Novosibirsk are given in the following table:

Kaon Form Factors (from a compilation of B. Bartoli et al., Rivista Nuovo Cim. 2, 242 (1972))

Values at the ϕ mass

	ACO	Novosibirsk
$\sigma(e^+e^-\to K^+K^-)$	$(2.41\pm0.13)\cdot10^{-30}$	$(2.13\pm0.17)\cdot10^{-30}$ cm^2
σ(all modes)	$(4.99\pm0.40)\cdot10^{-30}$	$(3.96\pm0.35)\cdot10^{-30}$ cm^2
Γ_ϕ	(4.09 ± 0.29)MeV	(4.67 ± 0.42)MeV
$\Gamma(\phi\to e^+e^-)/F\ (\phi\to$all)	$(3.52\pm0.28)\cdot10^{-4}$	$(2.81\pm0.25)\cdot10^{-4}$
$\Gamma(\phi\to e^+e^-)$	(1.44 ± 0.12)KeV	(1.31 ± 0.12)KeV

In addition to the above-mentioned series of measurements which refer to energy regions such that $q^2 \lesssim 1$ (GeV/c)^2, in the recent past data have become available outside the ρ, ω, ϕ vector meson region. These data essentially come from Adone and cover the four-momentum square region ranging from 1.4 to 9 (GeV/c)^2.

The results from this generation of experiments suffer either from difficulties encountered in separating π's and K's (no magnet used), or from the very low values of the cross sections (few nanobarns). In spite of this, interesting results have been reached in Frascati either for the π or for the K^+ form factor |13|.

As far as the K^- is concerned it has been recently proved (M. Bernardini et al., Adone BCF) that time-like photons produce K pairs with rates that are comparable with the ones for π pairs, so that a first set of data about the $K^\pm$ form factor is available. The experimental principle of this measurement is the identification of the K's by range comparison with pions (at the Adone energies the two equal body final state particles have definite energy and in $\sim$90% of the cases one or the other of the K mesons reach the end of their range without a nuclear interaction. This allows a discrimination against pions). This kind of π/K discrimination works up to $q^2 \simeq 3$ (GeV/c)^2. Above this value and up to 9 (GeV/c)^2 a separation π/K has been made on a theoretical basis (according to an estimate made

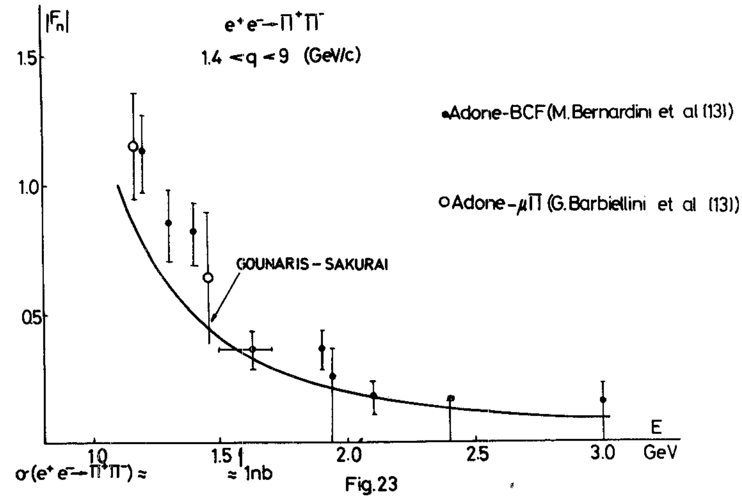


Fig.23

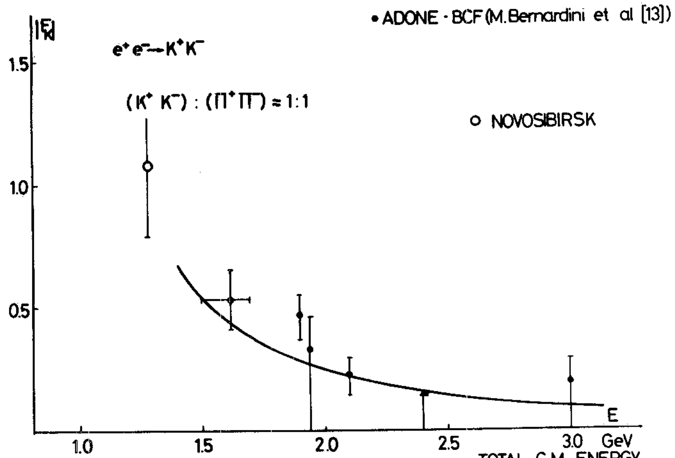


Fig.24

by N. Cabibbo, making use of SU(3) and linear, zero width, pole terms for known vector mesons), which proves to be in agreement with experimental data in the energy region where the comparison π/K can be made experimentally. Experimental results are shown in Figs. 23 and 24.

The Gounaris-Sakurai fit which is reported together with the data of $|F_\pi|$ is in reasonable agreement with experimental data. The systematic tendency of the points in the region E $\sim$ 1.2-1.5 GeV could be explained either in terms of other vector mesons with the same quantum numbers of the ρ (ρ', ρ'' etc.) or in terms of a ρ meson propagator with a different high-energy behaviour (for references see Gourdin's report at the 1973 Bonn Conference).

Proton form factor

The first measurement of the $e^+e^- \rightarrow p\bar{p}$ reaction was performed at Adone |14|. On the basis of (25$\pm$6) events at q^2= 4.4 (GeV/c)^2 collected at a rate of the order of 1 event/day a cross section

$$\sigma(e^+e^- \rightarrow p\bar{p}) = (0.91 \pm 0.22) \text{ nb}$$

was obtained.

After this first-generation experiment, other more complete and systematic measurements are planned to be performed in the near future either at Adone or at Spear.

IV. MANY-HADRON PRODUCTION IN e^+e^- ANNIHILATION PROCESSES AT HIGH ENERGIES

A very interesting result of the first series of experiments performed at Adone has given evidence for an abundant e^+e^- production of many-hadron states. A term of comparison for this abundance is the fermion point-like pair production ($e^+e^- \rightarrow \mu^+\mu^-$) cross section.

This result (references in K. Strauch's talk at the 1973 Bonn Conference, and V. Silvestrini, the 1972 Batavia Conference) was found at Adone (1971) and has been recently confirmed at higher energies (5 GeV) by the CEA people |15|.

It is worth remembering that the experimental arrangements of the first generation of apparata active at Adone (the so-called $\mu\pi$, Boson, $\gamma\gamma$, BCF) were not properly designed to face the unexpected abundant production of many-body final states. In particular, the rather small solid angle covered by the set-ups ($\Delta\Omega/4\pi \simeq$ 20% typically) made detectable only a limited fraction of the produced particles: the lack of knowledge of the momenta of the detected particles (no magnetic analysis available) did not allow a proper estimate of what was missing of the reaction products. Therefore, apart from some particular case, there was a substantial lack of knowledge of multiplicities and content of the various reaction channels.

Thus, in order to estimate production cross sections from the rough data, a certain number of assumptions had to be made, all this resulting in somewhat model-dependent analyses.

In spite of these difficulties a certain number of interesting results has been achieved.

IV.a. Identification of particular reaction channels

The $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ has been kinematically isolated (Adone-$\mu\pi$) and its energy behaviour inspected in the total c.m. energy region 1.2-2.0 GeV (see Fig. 25). The production cross section for this particular channel shows a peak, with almost no background, centered around an energy of 1.6 GeV. This behaviour, together with other experimental information, was interpreted as a strong support in favour of the existence of a higher mass vector meson (ρ') with the same quantum number of the ρ meson. Our present knowledge about the ρ' meson is summarized in the following table. (See Moffeit's report to the 1973 Bonn Conference).

About the existence of the ρ' meson

Reaction	J^P	I^G	M (MeV)	Γ (MeV)	
$e^+e^- \to \rho' \to \rho^0\pi^+\pi^-$ Adone	1^-	1^+	$\sim$1600	$\sim$300	$\sigma_{peak} \simeq 20$ nb
$\gamma p \to \rho' p$, $\rho' \to \rho^0\pi^+\pi^-$ SLAC-pol. γ beam	1^-	1^+	1500; $\frac{\Gamma(\rho'\to\pi^+\pi^-)}{\Gamma(\rho'\to all)} < 0.2$	$\sim$600	$\sigma \simeq 1.6\mu b$
$\pi^-p \to \pi^+\pi^- n$ (CERN, ρ' inelasticity)	1	1	1590$\pm$20	180$\pm$50	$\pi\pi$ phase shift analysis

$$\frac{\Gamma(\rho'\to\pi^+\pi^-)}{\Gamma(\rho'\to all)} = 0.25 \pm 0.02$$

(influence the π e.m. form factor)

Another interesting result has recently been reported from ACO where the reaction $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ has been detected and the behaviour of its cross section as a function of the measured energy |16|. The energy threshold effect in $\pi^+\pi^-\pi^0\pi^0$ production is obviously in

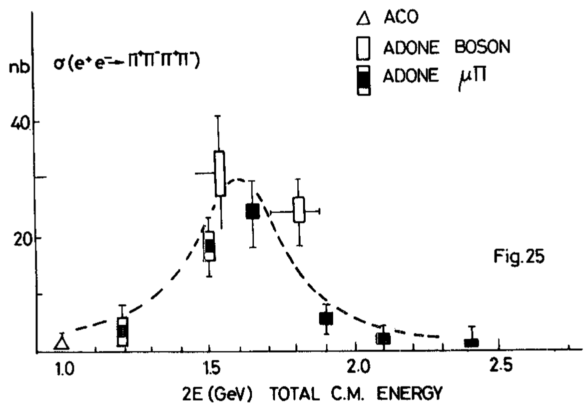


Fig.25

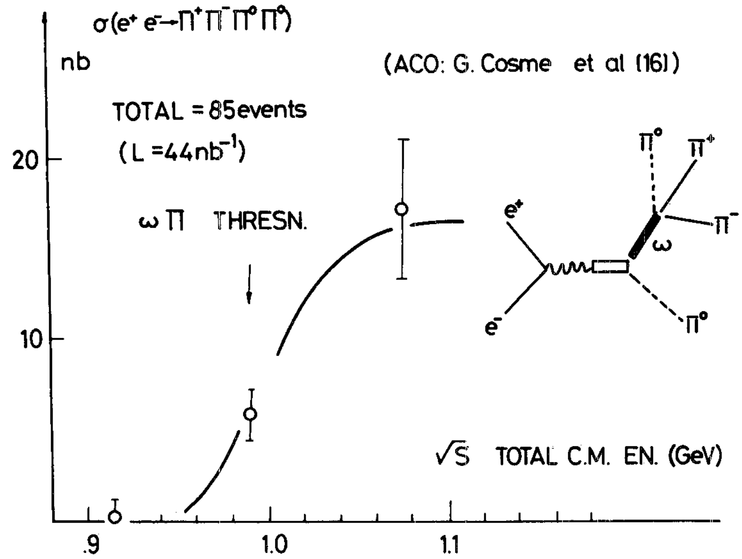


Fig.26

good agreement with what has been expected on the basis of the two-body production $e^+e^- \to \omega^o\pi^o$ ($\omega\pi^o$ threshold at 919 MeV) and VDM. This point has to be further tested, since recent results from SLAC (Moffeit's report at 1973 Bonn Conference) on the photoproduction reaction $\gamma p \to p\pi^+\pi^-$ + (neutral missing mass higher than 1 m_π) show a clear enhancement at $M(\pi^+\pi^- + \geq 2\pi^o) \approx 1250$ MeV and give the indication of a preferred $\omega^o\pi^o$ final state at this energy. These elements might be the first support to the evidence of another (ρ'') vector meson of a mass around 1.2 GeV.

IV.b. Total cross section for the reaction $e^+e^- \rightarrow$ many hadrons

It has been proved that the many-body reactions so far observed involve mainly hadrons (nonshowering behaviour, pulse-height analysis in scintillation counters, nuclear interactions, etc.) with very small possible contaminations from μ's or e's (< 10%). However, a distinction between π's and K's has not been achieved.

It can also be stated that the dominant production mechanism is the one-photon annihilation channel (two-photon processes have been detected and their possible background on a many-hadron sample, evaluated). A typical statistical situation is shown in Fig. 27.

$e^+e^- \rightarrow$ many hadrons
Typical statistics (only recent data)

Experiment	$\sqrt{s}$ GeV	Number of events	Cross sections
Adone $\mu\pi$	2.85	523	$\sim$ 18 nb
Adone $\gamma\gamma$	2.95	179	$\sim$ 24 nb
CEA	4.0	88	$\sim$ 27 nb
CEA	5.0	108	$\sim$ 22 nb

Fig. 27

Now, in order to evaluate cross sections from rough data, due to the above-mentioned limitations, a certain number of assumptions has been made by experimental groups involved in these studies. One possibility is to assume an invariant phase space momentum distribution for the produced particles, to neglect kaonic channels and to solve a system of equations which link the number N_c of events detected in a certain configuration c (for instance, 1 charged + 2 photons, 2 charged + 1 photon, 3 charged, etc.) to partial cross sections σ_i's. That is the system

$$N_c = L \sum_i \sigma_i \varepsilon_{ic} ,$$

where L is the total integrated luminosity and ε_{ic} is the efficiency to detect in a configuration c an event from the i-th process whose partial cross section is σ_i. (This is the procedure followed by the Adone boson, Adone $\gamma\gamma$, Adone $\mu\pi$ and CEA groups). Due to the rather poor statistics collected and to the requirement that the σ_i's from the solution of the system $N_c = L \sum \varepsilon_{ic}\sigma_i$ have to be positive, the "optimal" solutions are such that partial cross sections σ_i are not well determined, whereas the total cross section $\sigma_T = \sum \sigma_i$ is much more reliable.

Another approach (followed by the Adone-BCF and for the 2.85 GeV points by the Adone-$\mu\pi$ group) consists in assuming that the relative weights of partial cross sections in the e^+e^- annihilation into hadrons are the same as in the case of $p\bar{p}$ annihilation in the corresponding energy region. Furthermore, an invariant phase space momentum distribution is also assumed.

The results of the analysis performed on these lines are shown in Fig. 28 (where some grouping of nearby points has been done). The ratio $R = [\sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)]$ is also reported (Fig. 29) as a function of $s = (2E)^2$ for $s > 3$ (GeV)^2.

It appears clear that the ratio R is larger than 1 in the region $3 < s < 9$ (GeV)^2 and substantially larger than 2 at energies $9 < s < 25$ (GeV)^2.

In Fig. 30 the average charge multiplicities as a function of energy are also given.

It is evident that a substantial improvement must be achieved for measurements. It is not only a matter of statistics but clear requirements must be fulfilled by the second generation of experiments (identification of every reaction channel, determination of rates among channels, study of correlations among final-state particles, etc.) in order to disentangle questions which are just showing up. In this way it will be possible to reach positive conclusions on the many hadron production via the one photon annihilation channel whose interest is known to move from the problem of the structure of hadrons and its connection with the deep inelastic lepton scattering.

V. FUTURE DEVELOPMENTS

The physical motivations for further researches on the e^+e^- induced reactions are in a way obvious and very naturally following the indications so far obtained and presented in the previous sections. It is almost useless to recall that some of the most interesting experimental results of the recent past, such as the deep inelastic electron scattering at SLAC, or the e^+e^- annihilation in many hadrons at Adone and CEA, or the neutrino-nucleon collisions at NAL or CERN (Gargamelle) have shown how the use of point-like probes carrying known interactions is necessary in order to reach a really deep insight, relatively free from secondary effects, in the world of hadronic matter.

It is clear that in this context the role of the electron-positron colliding beam storage rings is fundamental and unique. Some of the main subjects which such high-energy machines will be able to

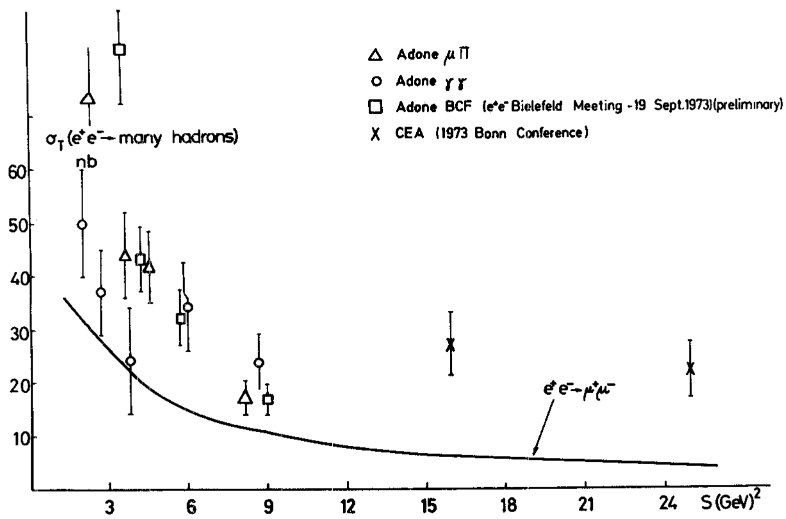

Adone μπ
Adone γγ
Adone BCF (e⁺e⁻ Bielefeld Meeting -19 Sept.1973)(preliminary)
CEA (1973 Bonn Conference)
σT (e⁺e⁻→ many hadrons)
nb
60
50
40
30
20
10
e⁺e⁻→μ⁺μ⁻
3
6
9
12
15
18
21
24
S (GeV)²

Fig. 28

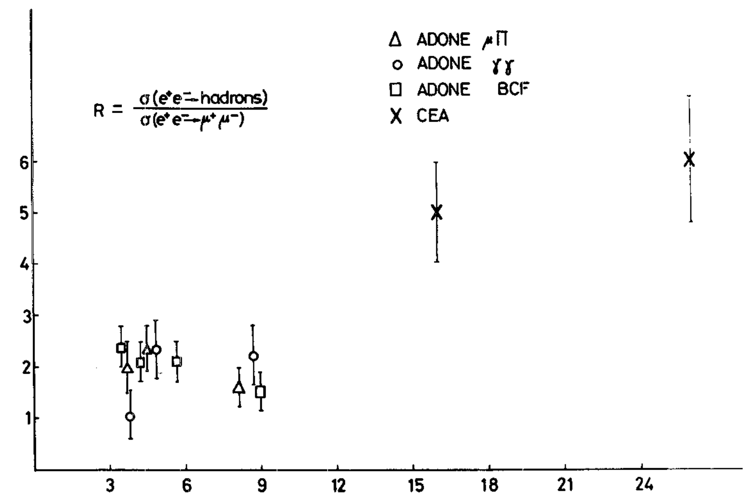

ADONE μπ
ADONE γγ
ADONE BCF
CEA
R = σ(e⁺e⁻→hadrons) / σ(e⁺e⁻→μ⁺μ⁻)
6
5
4
3
2
1
3
6
9
12
15
18
21
24

Fig. 29

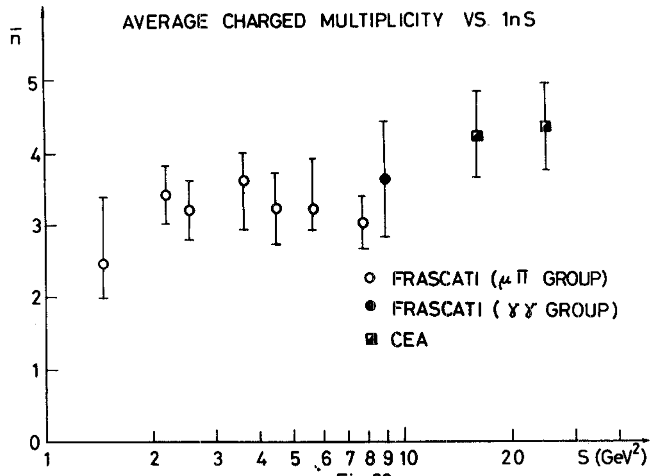

AVERAGE CHARGED MULTIPLICITY VS. 1n S
n̄
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
20
S (GeV²)
FRASCATI (μ π GROUP)
FRASCATI (γ γ GROUP)
CEA

Fig. 30

cover are the following:

- structure of the electromagnetic current of the hadrons;
- many hadron states of pure angular momentum (production cross sections and multiplicities as a function of the total c.m. energy);
- search for leptonic-like particles (constituents, heavy leptons, etc.) up to large masses;
- Q.E.D. studies;
- weak electromagnetic interference effects (enhanced by the beam polarization);
- semi-inclusive processes.

In this perspective it is clear that the energy and the luminosity of a future electron-positron storage ring play an essential role. As far as the energy is concerned an immediate term of reference is the total c.m. energy. In the next table the present situation of the available c.m. total energies W (GeV) is shown for some of the various operating accelerators.

Machine	Reaction	W (GeV)
Adone	e^+e^-	3
Spear I (SLAC)	e^+e^-	5
SLAC (20 GeV)	ep	7
PS CERN	pp	7
NAL (400 GeV)	pp	28
ISR CERN	pp	60

Thus, for instance, a 2x15 GeV e^+e^- storage ring would provide for the many-hadron production channels more or less the same c.m. energy as NAL or SPS-CERN could produce in the pp → hadron reactions when working at 400 GeV.

As far as the luminosity is concerned, values of the order of 10^{32} $cm^{-2}s^{-1}$ are presently conceivable and this would be adequate to give largely satisfactory counting rates for the most relevant channels: for instance, around 20 GeV total c.m. energy the counting rate for the reaction $e^+e^- \rightarrow \mu^+\mu^-$ would be of 1 event/min, whereas a cross section of 10^{-4} nanobarn would give typical rates of 1 event/day.

A very high interest in the field of e^+e^- storage ring developments is widely diffused in the world, so that a series of feasibility studies has been started in several laboratories and a certain number of preliminary projects are already under the first approval procedure. It is enough to quote the e^+e^- 2x15 GeV ring designed at SLAC as a first step toward a more complete P.E.P. device which should hopefully include an electron-proton storage ring; or the Frascati SuperAdone (2x(10÷12) GeV e^+e^- ring which should make use of Adone as an injector; or the first stage of an English, large e-p project (EPIC) which should be a 2x14 GeV e^+e^- storage ring built within the Rutherford laboratory; or the German project PETRA with its 2x20 GeV e^+e^- colliding beams foreseen in the Hamburg-Desy area.

This trend seems to indicate that a very high energy colliding beam facility will play, in a not too far future, a significant role in the development of high energy physics.

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