ELECTRON-POSITRON INTERACTIONS

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I. Introduction

You already know from the title of this talk that it has much to do with the electromagnetic structure of the hadrons in the time-like region.

The knowledge of the hadron structure, which is responsible in large part for the phenomenology of the short-range hadron-hadron interactions, is probably preliminary to our understanding of the elementary-particle interactions. This gives particular relevance to this line of investigation.

However, the interpretation of the experimental information on lepton-hadron interactions in terms of hadron structure, in both the space-like and time-like region, requires three assumptions whose experimental foundations are worth discussing. This will be done in the first part of this paper, after some further introduction. The three assumptions are as follows:

1. Leptons behave as point-like Dirac particles. In particular, their current is the simple bilinear operator $\bar{\psi}\gamma_\mu\psi$.

2. The electromagnetic field is described by the Maxwell equations. In Feynman perturbation language, the photon propagator is simply given by its inverse four-momentum squared, $1/q^2$.

3. The electromagnetic interactions of leptons are well described by the first approximation, one photon exchange diagrams.

For those who are not familiar with this field, let me briefly recall the consequences of the validity of the above assumptions in terms of the hadron structure. Some of them are so well known that you might even be offended:

(a) The cross section for elastic lepton-hadron scattering is written in terms of matrix elements of the electromagnetic (e.m.) current associated with target hadron.[1] In turn, as a consequence of the validity of gauge and Lorentz invariance, the matrix elements of the e.m. current are written in terms of a small number of form factors which summarize the e.m. structure of the hadron considered as a whole. The form factors are functions of q^2; they are explored for space-like (negative) values of their argument in the scattering experiments.

(b) The cross section for hadron-antihadron ($h\bar{h}$) pair production from e^+e^- interactions can also be expressed in terms of current matrix elements and form factors,[2] which are therefore explored in e^+e^- experiments for time-like (positive) values of their argument. While the hermiticity of the e.m. current implies that the form factors are real in the space-like region, they are in general complex in the time-like region.

(c) For inelastic lepton-hadron scattering, once only the scattered lepton is detected (inclusive reactions) the cross section can be written in terms of matrix elements of current commutators.[3] The analogs of the form factors are usually called structure functions in this case and are functions of two invariants (e.g., q^2 and $\nu = E - E'$, the energy released by the lepton to the target hadron). The appearance of the variable ν is due to the fact that as you break or excite the target, its structure has also a time evolution.

(d) The total cross section for hadron production in e^+e^- interactions can also be expressed in terms of current commutators;[3] in particular, the Schwinger terms of the current commutators can be expressed as follows:

$$C^3 = \frac{1}{16\pi^3\alpha^2} \int_{4m_\pi^2}^{\infty} s\sigma_V ds \tag{I.1}$$

$$C^8 = \frac{3}{16\pi^3\alpha^2} \int_{9m_\pi^2}^{\infty} s\sigma_s ds. \tag{I.2}$$

The index (3;8) is an SU(3) index; $s = q^2$ when $q^2 > 0$, and C^i are the vacuum expectation values of the Schwinger terms; $\sigma_s(\sigma_V)$ is the total cross section to produce a hadron system with isospin $I = 0$ ($I = 1$).

(e) Inclusive spectra of hadrons produced in e^+e^- interactions are related to current products[3] (not to current commutators, unless specific restrictive models are used).

After the above short review of the correspondence between hadron structure and specific experimental information, let me make a few comments about the experimental information itself.

The data are produced at machines like the one shown in Fig. 1. A beam of bunches of electrons is captured in the doughnut and circulates in one direction with a lifetime of many hours, hitting bunches of positrons, which circulate in the opposite direction in as many "interaction regions" as the total number of bunches.

The machine intensity is measured by the so-called "luminosity" L defined as follows:

$$\dot{n} = L\sigma, \tag{I.3}$$

where $\dot{n}$ is the rate over the full solid angle of events from a reaction whose cross section is σ. L is usually monitored by measuring events from a process of known cross section (e.g., small-angle e^+e^- scattering, double bremsstrahlung etc.).

In terms of the machine parameters, L is proportional to the products of the beam currents divided by their effective area A

$$L \propto \frac{i^+ i^-}{A}.$$

At Adone, a luminosity of $0.5\times10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is usually obtained at energies between 1 and 1.5 GeV per beam, and $(1\text{-}1.5)\times10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been recently obtained during machine test runs. The CEA bypass, whose first results have appeared at this conference, has worked with $L = 0.3\times10^{29}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. At SPEAR, not yet used for experiments, $L = 2\times10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been obtained at 1.5 GeV, and they hope to gain another order of magnitude, especially at higher energy (~2 GeV). The current densities to obtain the above luminosities are however so high that the machine operation becomes quite critical, and for comparison let me recall that a luminosity of $10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponds to the Stanford linac beam against a hydrogen target $10^{-2}\,\mu$ thick!

In addition, the cross sections for hadron production from e^+e^- interactions are extremely small. At Adone energies:*

$$\sigma(e^+e^- \to \pi^+\pi^-) \qquad \text{a few nanobarns } (10^{-33}\,\mathrm{cm}^2)$$
$$\sigma(e^+e^- \to p\bar{p}) \qquad \text{a fraction of nanobarn} \tag{I.5}$$
$$\sigma(e^+e^- \to \text{total hadron}) \quad 30\text{-}60 \text{ nanobarns.}$$

With ideal detection apparatus covering the full solid angle with 100% efficiency, a few counts/hour are thus expected. In practice, counting rates of a few events/day or even few events/week are not unusual, and with detection apparatus, quite large, heavy and complicated.

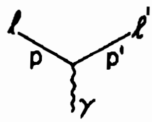
We can therefore conclude that the simplicity of interpretation of the data, which is related to the possibility of expressing the cross sections in terms of fundamental phenomenological functions, is counterbalanced by the experimental difficulties deriving from the unusually small counting rates.

In spite of these difficulties, and although this line of investigation has been pursued up to now for only a few years in the laboratories of Novosibirsk, Orsay, and Frascati, and only recently at CEA, the experimental information has already produced a great amount of interest.

II. Validity of the Underlying Hypothesis

The first interesting result of e^+e^- interaction experiments is a test of the validity of the hypotheses (specified in the previous section) which allows one to interpret the cross sections in terms of hadron structure.

Let us first consider the first two hypotheses, namely that in the graph



(ℓ and ℓ', the initial and final lepton, being both on their mass shell) the vertex function Γ_μ and the photon propagator S_γ can be written according to the rules of pure QED:

$$\Gamma_\mu = \gamma_\mu \tag{II.1}$$

$$S_\gamma = \frac{1}{q^2}, \quad (q_\mu = p'_\mu - p_\mu). \tag{II.2}$$

The most general modifications of QED allowed in this case by gauge and Lorentz invariance are[1,4]

$$\Gamma_\mu = \gamma_\mu F_1(q^2) + \sigma_{\mu\nu} q^\nu F_2(q^2) \tag{II.3}$$

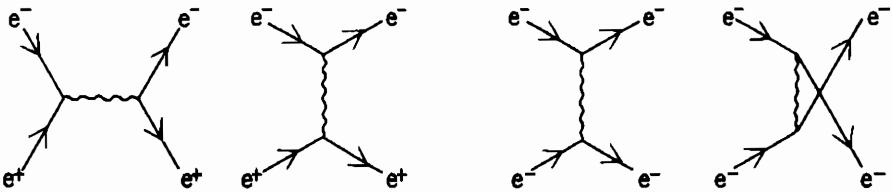
$$S_\gamma = \frac{M(q^2)}{q^2}. \tag{II.4}$$

The restrictions on F_1, F_2, and M required on general principles[4] are not relevant in this context. The g-2 experiments[5] allow us to conclude that $F_2(q^2) = 0$ within an accuracy which, from

*For comparison, let me recall that at ISR energies typical p-p cross sections are six orders of magnitude larger.

our present point of view, is exact. Therefore, testing our two hypotheses (II.1) and (II.2) means testing that $F_1(q^2) = 1$ and $M(q^2) = 1$. This can be done by measuring the e^-e^- and e^+e^- elastic-scattering cross sections.

The e^-e^- (Møller[6]) and e^+e^- (Bhabha[7]) elastic scattering are described at first order by the following graphs.



Bhabha **Møller**

If QED is modified according to (II.3) and (II.4), the amplitude corresponding to each graph is proportional to $M(q^2)F_1^2(q^2)$, but since q^2 is not the same for the two graphs contributing to each process, the ratio $R = \sigma_{exp}/\sigma_{QED}$ is not equal to $|M^2(q^2)F_1^1(q^2)|^2$. However, in the kinematical regions explored by the experiments, one graph (the one corresponding to the lower value of the momentum transfer squared q_ℓ^2 (space-like in both Møller and Bhabha scattering) dominates the other so that R is approximately equal to $|M(q_\ell^2)F_1^2(q_\ell^2)|^2$.

The experimental results available prior to this conference are shown in Fig. 2.[8-13] In the e^-e^- Stanford I[10] and Stanford II[12] experiments, the absolute value of the cross section is not measured; therefore, the average value of R has been normalized to one. In the Orsay point[11] and in the Frascati data,[8,9,13] in addition to the statistical error (bars), I have displayed also the systematic uncertainty (boxes), including the overall normalization uncertainty.

In Fig. 3, the new data presented at this conference by the BCF group,[14] working at Adone, are shown. The authors prefer to present their data in terms of the yield per unit integrated luminosity, y, as a function of s. Both absolute value and s dependence of y are in excellent agreement with the predictions of QED; the absolute value to within ±4%, while the s exponent which QED predicts equal to one, is experimentally 0.985±0.04.

Finally, the first preliminary analysis of the CEA e^+e^- wide-angle events (~200 events) gives:[15]

$$R = \sigma_{exp}/\sigma_{QED} = 0.89 \pm 0.10$$

(radiative corrections not yet applied) at a total energy of 4 GeV.

We can conclude from the above data that R is equal to 1 within ±4-5% up to q^2 (space-like) $= 2\,(\text{GeV}/c)^2$, and to within ±10% up to $q^2 = 7\,(\text{GeV}/c)^2$.

Let us now consider the experimental test of the point-like leptons and $1/q^2$ photon propagator in the time-like region. This has been done by measuring the process $e^+e^- \to \mu^+\mu^-$ which proceeds via the single annihilation graph (time-like photon). The results in terms of the ratio $R = \sigma_{exp}/\sigma_{QED}$ are presented in Fig. 4.[16-18]

In terms of possible modification of the lepton-photon vertex function and of the photon propagator, R can be written as $R = |F_e(s)|^2 \cdot |F_\mu(s)|^2 \cdot |M(s)|^2$. R is equal to one within the large experimental errors (typically ±15-20%) up to $s = 4.4\ \mathrm{GeV}^2$. These QED data are often parametrized in terms of a cutoff parameter Λ by assigning the form $[1 - (q^2/\Lambda^2)]$ to either the lepton form factor or to the photon propagator modification M. This parametrization was first introduced at low q^2 in order to interpret the data in terms of upper limits on the radius of the charge distribution. It is, however, arbitrary at high q^2 (where the interpretation of the form factors as Fourier transforms of spatial distributions is impossible) and sometimes even gives rise to serious theoretical difficulties (when assigned, for instance, to M or to a lepton propagator); however, it is usually justified with the need of comparing different experiments. This attitude is misleading in my opinion. It invites one to consider a rough experiment at high energy equivalent to a good precision low-energy experiment because in the cutoff philosophy possible deviations from QED are expected to increase with increasing energy. This might very well not be the case.

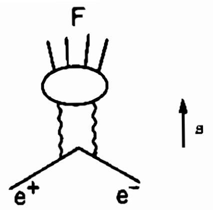
A very nice experimental example is shown in Fig. 5 representing the results of another experiment[19] on reaction $e^+e^- \rightarrow \mu^+\mu^-$ performed at Orsay at an energy that is lower than that of the data of the previous figure.

Although at the limit of the experimental errors, a deviation of R from one is showing up. The energy range explored is around the ϕ mass, and the effect observed is due to vacuum polarization. The fact that we are not surprised, and we do not claim with great emphasis that a breakdown of QED is being discovered, is only due to the fact that the ϕ meson has already been discovered.

The relevant point in QED experiments is to compare experiment with theory and possibly discover new phenomena; it is not to compare experiments (or experimentalists) among themselves. The best parameter, at whatever energy, is the precision of the experiment rather than the cutoff parameter.

Let us finally consider the third hypothesis, i.e., the one-photon exchange approximation. Due to the smallness of the electromagnetic coupling constant $\alpha = 1/137$, the one-photon exchange diagrams are expected apriori to dominate the transition amplitudes. In the space-like region, experimental tests of this hypothesis have been performed through cross-section measurements (Rosenbluth plots), by comparing e^+ and e^- elastic-scattering cross sections and by measuring the recoil proton polarization, as well as the asymmetry in the scattering of leptons on polarized targets.[20] This is not, however, among the objects of this paper. Let me only recall here that the one-photon exchange hypothesis holds only approximately, and its experimental proof is to be considered as a demonstration of the absence of strong-enhancement mechanisms in the diagrams with two virtual photons exchanged,[21] so that the evaluation of the usually small contribution from higher-order graphs can be performed by means of standard-calculation techniques (radiative corrections).[22]

In the time-like region, the smallness of the usual two-photon exchange contribution has not been experimentally tested. It is worth noticing that in the time-like region the number of exchanged virtual photons is directly related to the charge conjugation eigenvalue C of the final state. If the charge of the produced particles is not recognized (as it was the case for all the experiments performed up to now with e^+e^- storage rings) then the interference between even and



(II.5)

odd states of C cancels so that the two-photon exchange influence is expected to appear at order α^2 rather than α as in the space-like region. While waiting for experimental tests, we can therefore reasonably well assume, for the moment, that the contribution from graph (II.5) can be neglected.

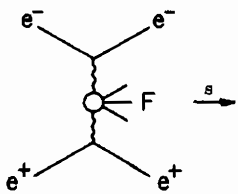
I would like, however, to put forward a warning about higher-order contributions. Let me list three points:

1. Each graph is depressed of an α factor with respect to the lower-order ones, but the number of graphs increases rapidly with the order.

2. Higher-order graphs can often involve lower values of the momentum of the virtual particles which can at least partially compensate for the additional α factor.

3. The calculation of higher-order contributions is usually very complicated; this too often invites drastic and inadequate approximations.

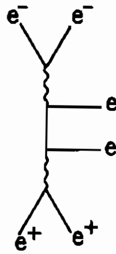
I am again in the position of giving you an experimental example. Many authors[23] have called our attention to processes described by the graph



(II.6)

The cross section corresponding to this graph is depressed of a factor α^2 with respect to the usual annihilation graphs. However, the two virtual photons can have very small q^2 which can compensate for the α^2 factor. It is well known that while the usual annihilation processes are expected to decrease with increasing energy (most likely as $1/s$) these processes (II.6) are expected to have logarithmically increasing cross sections and to overtake the annihilation processes around a total energy of some GeV, representing a dangerous background on one side and an interesting field of investigation on the other for higher-energy storage rings.

Below 3-GeV total energy, the contribution of these processes is usually quite small and concentrated in kinematical regions which do not practically overlap with the one-photon annihilation channels. The contribution of the simplest among the graphs (II.6), namely (II.7), is however large enough to allow experimental investigation with a counting rate appreciable (20-30%) with respect to the lower-order, one-photon exchange processes. Experiments have been performed at Novosibirsk[24] and Frascati.[25]



(II.7)

The results of the Frascati $\gamma\gamma$-group are shown in Fig. 6 and are compared with theoretical calculations. Two of the leptons, emitted at large angle with respect to the beam direction, are detected in the main apparatus while a third one, emitted approximately along the beam direction, is bent by one of the machine magnets and detected by an additional counter. This allows one to define the sign of β, the c.m. velocity of the large-angle emitted pair, as shown in the upper part of Fig. 6. The fourth lepton, also emitted at small angle, usually escapes detection.

The number of events is plotted in Fig. 6 as a function of β. The distribution is in very bad agreement with the calculation performed with the usual equivalent photon approximation[23] (dashed line), and although it depends quite critically on the efficiency of detection of the apparatus ϵ, no value of ϵ can be chosen which makes the agreement acceptable. G. Parisi[26] has estimated that most of the events are due to a kinematical configuration in which the virtual lepton and one of the virtual photons (rather than both virtual photons) are close to their mass shell (full-line).

Even in the case of QED, a well-established theory, for higher-order contribution we sometimes find the same situation as in strong interactions, namely of theoretical calculations fitting, rather than predicting, the experimental data.

However, at the present level of errors in the hadronic cross sections, the radiative corrections are well enough known, and the contribution from graphs (II.6) is experimentally discriminated. So hereafter, to interpret the hadronic data which I am going to present, the validity of the three above hypotheses can be assumed. For a correct interpretation of more precise data, especially from higher-energy storage rings, a careful evaluation of all higher-order contributions is very important.

III. Proton Form Factors

A first measurement of the cross section for reaction

$$e^+e^- \to p\bar{p} \qquad \text{(III.1)}$$

has been performed at Frascati by the Naples[27] group; 25 ± 6 events from reactions (III.1) have been observed at $s = 4.4\ \mathrm{GeV}/c^2$. The discrimination against background is achieved using E and dE/dx measurements (range and specific ionization in thick scintillation counters), time-of-flight determination, and geometrical requirements in optical spark chambers; the resulting sample is very clean, in spite of the extremely low counting rate: 1 good event/(2-4) days. On the basis of Monte-Carlo calculations, the authors expect to observe an antiproton annihilation star in 50% of the cases, and the events in which the annihilation star is actually observed are 12.

To determine the total cross section from the observed events and total integrated luminosity ($\int L\, dt = 1.9 \times 10^{35}\, cm^{-2}$ for this experiment), extrapolation of the counting rate over the full solid angle is needed.* For this purpose the angular distribution of the events must be known.

The equivalent of the Rosenbluth formula in the time-like region is:[2]

$$\frac{d\sigma}{d\Omega} = \frac{\pi\alpha^2}{4}\frac{\beta p}{s}\left[|G_M|^2(1+\cos^2\theta) + \frac{4M^2}{s}|G_E|^2\sin^2\theta\right]$$
$$\sigma = \frac{4\pi\alpha^2}{3}\frac{\beta}{s}\left(|G_M|^2 + \frac{2M^2}{s}|G_E|^2\right) \tag{III.2}$$

This formula is little enough dependent on θ so that the authors are able to quote a model-independent value of the cross section.

$$\sigma(e^+e^- \to p\bar{p}) = (0.91 \pm 0.22)\, 10^{-33}\, cm^2$$
$$s = 4.4\ GeV/c^2. \tag{III.3}$$

This result is plotted in Fig. 7 where it is compared with previously available upper limits from reaction $p\bar{p} \to e^+e^-$ [28, 29] and with some naive predictions.

Some information on the proton electromagnetic form factors G_E and G_M can also be inferred. Assuming $|G_M| = |G_E|$, as it should be at threshold,** one finds

$$|G_E| = |G_M| = 0.27 \pm 0.04.$$

Assuming alternatively $G_E = 0$ or $G_M = 0$, one finds respectively

$$G_E = 0, \quad |G_M| = 0.36 \pm 0.05$$
$$G_M = 0, \quad |G_E| = 0.46 \pm 0.07.$$

This is the first quantitative information about the nucleon form factors in the time-like region. We are witnessing the opening of a new field of systematic investigation. This will complement the experimental approach via electron-nucleon scattering whose pre-eminent contribution to our understanding of elementary particles is well known. The experiments in the time-like region via e^+e^- interaction, although unfavored from the point of view of counting rates, offer a unique possibility unaccessible to the scattering experiments--the possibility of measuring and comparing the form factors of unstable baryons.

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*The solid angle covered by the apparatus, as seen from the center of the interaction region, is (0.6) 4π sr. However, averaging over the extended source, the effective solid angle is reduced to (0.28) 4π sr.

**G_E and G_M are related to the Dirac and Pauli form factors F_1 and F_2 through the formula

$$F_1 = \frac{G_E - \tau G_M}{1-\tau} \qquad F_2 = \frac{G_M - G_E}{1-\tau} \qquad \tau = \frac{s}{4M^2}.$$

Unless G_E goes to G_M as τ goes to 1 (threshold condition), F_1 and F_2 diverge and the electromagnetic current of the proton therefore does the same.

IV. Pion and Kaon Form Factors

The cross section for production of a $B\bar{B}$ pair

$$\sigma(e^+e^- \rightarrow B^+B^-), \tag{IV.1}$$

where B is a spinless boson, is simply related to the single form factor describing the e.m. structure of B. This relation is[2]

$$\frac{d\sigma}{d\Omega} = \frac{\pi\alpha^2}{4}\frac{\beta^3}{s}|F_B(s)|^2 \sin^2\theta$$
$$\sigma = \frac{\pi\alpha^2}{3}\frac{\beta^3}{s}|F_B(s)|^2. \tag{IV.2}$$

A test of the $\sin^2\theta$ distribution (not yet experimentally performed) would allow one to test the one-photon exchange hypothesis.

Notice that a $\pi^+\pi^-$ system with $J = 1$ (as they have necessarily in the one-photon exchange hypothesis) must have $I = 1$ so that $F_\pi(s)$ is related to the coupling of isovector photons with hadrons.

Measurements of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ at $s \lesssim 1\ (\mathrm{GeV})^2$ have been quite extensively performed during the last 5 years at Novosibirsk[30] and Orsay.[31,32] The phenomenology is dominated by the production of the vector meson ρ, the foreseen interference term with the ω contribution (via the electromagnetic decay $\omega \rightarrow \pi^+\pi^-$) having also been observed. The results are summarized in Fig. 8 showing $|F_\pi|^2$ as a function of s.

The full-line is the Breit-Wigner fit to the Novosibirsk points. The dashed line is the best fit to the Orsay data using the Gounaris-Sakurai formula (Breit-Wigner modified for threshold effects) and including the $\omega \rightarrow \pi^+\pi^-$ contribution. At the ρ peak the cross section is $\sim 1.5\ \mu b$. In terms of ρ parameters, the results can be summarized as follows:

	Orsay	Novosibirsk
m_ρ (MeV)	775.4 ± 7.3	754 ± 9
Γ_ρ (MeV)	149 ± 23	105 ± 20
$\dfrac{\Gamma_\rho \rightarrow e^+e^-}{\Gamma_\rho \rightarrow \text{total}}$	$(4.0 \pm 0.5)10^{-5}$	$(5 \pm 1)10^{-5}$
$\Gamma_\rho \rightarrow e^+e^-$ (keV)	(6.1 ± 0.7)	(5.2 ± 0.5)

The difference in the parameters obtained at Novosibirsk is essentially due to the fact that the ω contribution is not taken into account in this case. Actually, the best fit to the Orsay points [which provides the additional information $(\Gamma_{\omega\rightarrow 2\pi}/\Gamma_{\omega\,\text{total}})^{\frac{1}{2}} = (0.2 \pm 0.05)$, the phase angle between the ω and ρ amplitudes being $\phi_{\omega\rho} = 87^\circ \pm 15^\circ$] appears also to fit the Novosibirsk data perfectly.

The results above 1 GeV are presented in Fig. 9.[33,34] Separation of π's from K's has not been generally achieved in the Frascati experiments so that the interpretation of $|F_h|$ of Fig. 9 as $|F_\pi|$ requires the hypothesis that the contribution to the counting rate from the channel

$e^+e^- \to K^+K^-$ is negligible. This hypothesis is experimentally supported only up to $s \approx 2.3\ (\mathrm{GeV})^2$. In fact, at the energy $E^+ + E^- = 1.5$ GeV, the Frascati "$\mu\pi$ group" has run part of the time with a Cerenkov counter in each of their telescopes and are therefore able to discriminate pions against kaons. Out of the ~12 collinear hadron pairs detected during that period, only one was identified as a K, the remainders being pions. We see that for $1 < s < 4.4\ (\mathrm{GeV})^2$, $|F_h|$ is larger--but not dramatically larger--than the expected contribution of the ρ tail and has approximately a $(1/s)$ dependence. We shall see that in multihadron production evidence is found in favor of the existence of a higher-mass (~1.6 GeV) vector meson ρ', and one may be surprised by the fact that no bump appears in the $e^+e^- \to \pi^+\pi^-$ channel. This is however expected on theoretical grounds, as independently pointed out by Gourdin[35] and by Korström and Roos.[36] The excess above the ρ tail is probably a reflection of the large total cross section for inelastic channels coupled by unitarity to the $e^+e^- \to \pi^+\pi^-$ reaction.

Consider now the reaction $e^+e^- \to K^+K^-$ whose threshold is at $2E = 0.99$ GeV. Just above threshold we find the ϕ meson, and here $|F_K|^2$ is dominated by the process $e^+e^- \to \phi \to K^+K^-$.[37,38] The production of ϕ mesons in e^+e^- interactions is well known, and a summary can be found in the Particle Data Group Tables.

Above the ϕ mass, only four events have been observed at Novosibirsk at three different energies,[32] in addition to the above-mentioned Frascati event. Just to give an idea of the order of magnitude, these results are presented in Fig. 10 in terms of $|F_K|^2$. The curve B.W. represents the Breit-Wigner tail of the ϕ; the other two curves also include the expected ρ and ω contributions and correspond to two extreme choices of the phase between the ρ, ω, and ϕ amplitudes. Of course, five events are not sufficient to draw any conclusion.

V. Multihadron Production

Up to $s = 1.1\ (\mathrm{GeV})^2$ multihadron production in e^+e^- collisions is almost entirely $\pi^+\pi^-\pi^0$ production via the isoscalar vector mesons ω and ϕ. The elegant and interesting results of the Orsay and Novosibirsk groups are well known;[37,38] a summary can be found on the tables of the particle data group.

On the basis of these data, hadron production above one GeV was expected to be very scarce and to represent a negligible phenomenon in the overall picture of the electromagnetic interactions of hadrons.

The first data presented two years ago at the Kiev conference by the Frascati "Boson"[39] and "$\mu\pi$" groups[40]--according to which there was a garden where a desert was expected--were therefore greeted with surprise and skepticism.

Around a total energy to 2 GeV the cross section for multiparticle production was found to be at least as large as the cross section for production of point-like fermion pairs. On the basis of pulse-height analysis, shower recognition, and investigation of the interaction properties in the spark-chamber plates, it was soon possible to conclude that the produced particles are essentially hadrons (π or K) with a contamination from e and μ which is at most 5-10%.[41-44]

In addition, we now know that the production occurs essentially via the annihilation channel with at most a small contribution (few per cent) from graphs of the type (II.6). This was achieved by direct search for events of the type (II.6)[45,25] characterized by the fact that the initial e^+ and e^- survive in the final state and by angular correlation study of the multiparticle events.[46]

After two years of experimental study, the preliminary investigation has been extended to a wider range and has become quantitative. In addition, the first detailed analysis of some aspects of this new phenomenon are now available. Let me now present the data.

In Fig. 11, $\sigma_T = \sigma_{total}(e^+e^- \to \text{multihadron})$ is presented up to a total energy 2E = 3 GeV.[41-44, 47, 48, 50] Although the points of the "$\gamma\gamma$-group" are systematically slightly lower than the others, the overall agreement among the results of different experiments is quite good. Since it is quite difficult to get out of these many data points a feeling of the general behavior of σ_T, I have averaged groups of points at similar energies to obtain the values of σ_T shown in Fig. 12. Here the total energy extends up to 4 GeV where we have the first result of the hard work performed at CEA during the last months and weeks.[15] In spite of the lower luminosity with respect to Adone, the use of a large solid-angle apparatus [$\sim 0.5\ (4\pi)$], fully digitized, has allowed the CEA group to collect and analyze in a rather short time 87 multihadron events.

Around 2E = 1 GeV (Orsay point) σ_T is still dominated by the channels $e^+e^- \to \pi^+\pi^- + (1 \text{ or } 2)\pi$ and is consistent with the tails of the ρ, ω, and ϕ mesons.[47] We then have a broad bump around 1.5 GeV where σ_T becomes larger than the cross section for the reaction $e^+e^- \to \mu^+\mu^-$. At higher energy ($2E \gtrsim 2$ GeV) σ_T continues to remain well above the cross section for production of point-like fermion pairs. Two hypotheses have been used in the analysis: (1) the detected hadrons are π's with no contribution from K's and (2) that angular and energy distributions are determined by phase space alone. However, all the groups have checked that the results would remain unaltered within the errors if the production occurs via quasi-two-body intermediate states ($A^\pm\pi^\mp$, $\omega\pi^0$, etc.). Notice that although statistics are reasonable (the data points correspond to a total of about 1500 multihadron events) the errors are quite large. This is due to the fact that σ_T comes from the contribution of many channels, each detected with different efficiency and which the experimental apparatus are able to separate only partially and statistically.

There are those who prefer to take a different approach, namely to have smaller (essentially statistical) errors at the expense of introducing some extra hypothesis in their analysis. This has been done by the BCF group,[14] who assume that the distribution of the multiplicity channels is the same as in $p\bar{p}$ annihilation at rest, with phase space corrections as the energy increases.

Under this hypothesis, the BCF group obtain the results in Fig. 13; these are not included in the average values of Fig. 12. As one can see, these results are well consistent with the data of the other groups. In Fig. 14 the results on σ_T are presented in terms of the ratio $R = \sigma_T/\sigma_{\mu^+\mu^-}$ which is a particularly convenient presentation in order to compare with models. Between 1 and 2 GeV one sees a bump through which a line has been drawn that suggests the existence of a resonance. I have done this deliberately, since, as you will see below, the analysis of some particular multiplicity channels gives good evidence in favor of the existence of a ρ' at exactly this energy. You see confirmed here that the BCF data points are in agreement with the others, apart from the point at 2.4 GeV which, although consistent within the errors with the average from the other groups, suggests a tendency of R to decrease to one with increasing energy.

Above 2E = 2.5 GeV, however, R goes on increasing. Notice that the box in the CEA point represents the systematic uncertainty and only the small bar is the statistical error so that, according to the authors, this point excludes (by two standard deviations) a value of R = 2 at 2E = 4 GeV.

For those who are not familiar with the field, let me explain in a few words why the results presented in Fig. 14 are important. As you know, large inelastic cross sections and scaling structure functions in electron-nucleon scattering have suggested two overlapping theoretical approaches to the hadron structure: the parton models and the more formal, flexible but less-defined approach of the light-cone singular-current commutators (LCSCC).[51] In both cases a connection between the space-like and time-like region is naturally expected, although specific crossed predictions require, in general, some extra hypothesis. Let me quote a third possibility, independently proposed by F. Renard[52] and by Bramon, Etim, and Greco[53] and suggested by the discovery of the ρ'--the extended vector dominance model (EVDM), based on the known vector mesons and an infinite set of daughters. Without any free parameter, Bramon et al. are able to reproduce the main features of both the time-like and space-like data, including precocious scaling.

However, unless R goes asymptotically to a constant, both the parton models and the LCSCC approach would be in trouble, losing at best the attractive feature of simplicity. Also, the present formulation of the EVDM predicts $R \not\Rightarrow$ constant, even if a way out is probably easier in this case.

In addition, the absolute asymptotic magnitude R_∞ of R is a relevant piece of information; it is connected with the normalization of the currents in the LCSCC approach, or, if you prefer parton models, then it is given by

$$R_\infty = \sum Q_i^2 + \frac{1}{4} \sum q_i^2 ,$$

where Q_i are the charges of the fermion partons and q_i the charges of the boson partons. In Fig. 14 the prediction of two of the most popular parton identifications are shown. The conclusion in my opinion is that below 2 GeV we are still in the resonance region while above 2 GeV the behavior of R, whose value appears to be anomalously large, is not yet well enough known to allow us to judge if an asymptotic region has been reached.

Let us now look to the experimental information about the different channels which contribute to σ_T. Let us first consider the channel $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ which is the cleanest from the experimental point of view, since the knowledge of the angles of emission of the pions allows a complete determination of the kinematics, although with a zero-constraint fit. In Fig. 15, $\sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-)$ is shown, and we see that it has the typical behavior of a resonance over practically no background.

The possible existence of a higher-mass vector meson was already suspected on the basis of previous photoproduction experiments,[54,55] and has recently found a confirmation in a bubble-chamber experiment with the back-scattered laser beam at SLAC.[56]

The e^+e^- production channel presents however some important advantages. First of all, the one-photon exchange hypothesis alone allows one to assign the quantum numbers $J^{PC} = 1^{--}$. The even number of decay pions tell one that it is an isovector (ρ'). The mass and width appear to be

$$m_{\rho'} = 1.6 \text{ GeV} \quad \Gamma_{\rho'} \approx 350 \text{ MeV}.$$

Then the total cross section is easily related to the inverse ρ'-γ coupling constant $f_{\rho'}^2$:

$$f_{\rho'}^2/4\pi = \frac{4\pi\alpha^2}{m_{\rho'}\Gamma_{\rho'}} \frac{1}{\sigma^{\rho'}_{peak}},$$

where $\sigma^{\rho'}_{peak}$ represents the peak cross section to produce the ρ', taking into account all the decay modes. In Fig. 16 we see a separation of $\sigma_{total}(e^+e^- \to \text{hadrons})$ in the even and odd G-parity states obtained by the Frascati "$\mu\pi$-group" by classifying the events according to whether an even or odd number of pions (including, of course, π^0's) is produced. This allows one to evaluate $\sigma^{\rho'}_{peak}$ (nonresonant background subtracted) as

$$\sigma^{\rho'}_{peak} = 45 \pm 15 \text{ nb},$$

and

$$f_{\rho'}^2 = 10 \pm 4.$$

Although with large errors, we thus already know

$$f_{\rho'}^2/f_{\rho}^2 \simeq 4.$$

Finally, the first preliminary investigation of angular correlations in the channel $\rho' \to \pi^+\pi^-\pi^+\pi^-$ tends to favor the decay mechanism[57]

$$\rho' \to \rho + \epsilon \to 4\pi.$$

A natural question is raised by the above results about the ρ': where are the isoscalar members of the ρ' nonet? Of course, I do not know the answer. Let me only bring attention to the fact that the data points are 100 or at best 50-MeV spaced. A narrow resonance would have most probably escaped detection. It is particularly important in my opinion to perform cross-section measurements with continuous sweeping of the storage-ring energy. As first suggested by C. Bernardini some years ago, a narrow resonance between two of the explored energies could appear.

Just to let people know what experimental information is available, let me display the presently known results about the other multiplicity channels in Figs. 17-22. As you see, not all the figures represent independent results; some show the sum of the cross sections corresponding to two or more multiplicity states.

A type of inclusive information which has been derived by different groups from the information contained in the previous figures is shown in Fig. 23 representing the average total multiplicity $\langle n \rangle_t$ and charged multiplicity $\langle n \rangle_{ch}$ as a function of energy. Both appear to increase very slowly with increasing energy. One may wonder how it is possible to obtain $\langle n \rangle_t$ and $\langle n \rangle_{ch}$ with relatively small errors out of the large-error points shown in the previous figures. This is due to a lucky numerical accident. Actually, since the channels $e^+e^- \to \pi^+\pi^-\pi^0$ and the channels $e^+e^- \to 6\pi$'s do not contribute much to the total cross section, a relatively rough knowledge of the cross sections to produce 4 and 5 π's allows one to determine, with a quite small error, an average value between 4 and 5.

This is all about the experimental information. I could now try to conclude this talk with a list of questions whose experimental answer would allow us to distinguish among the different theoretical approaches: do the structure functions scale, do the angular distributions show a double-jet structure? etc. I am convinced that without any explicit invitation, experiments will be able to do even better than that in the near future and produce a systematic phenomenological picture of multihadron production.

Most of the features of the presently available data were completely unforeseen and unsuspected when the experimental setups were designed and built. But now, new apparatus and higher-luminosity machines are ready to start measuring. I am sure that at the next Rochester Conference our knowledge of the e.m. structure of hadrons in the time-like region will make a jump forward.

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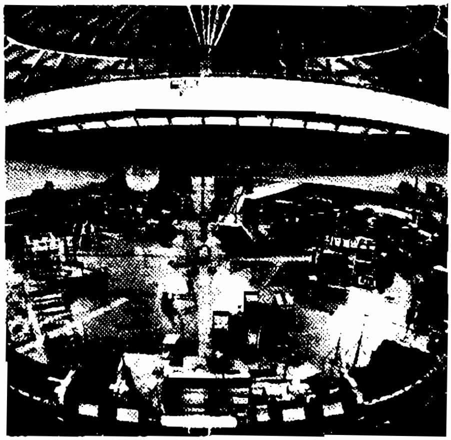


Fig. 1. View of Adone, the Frascati 2×1.5 GeV e^+e^- storage ring.

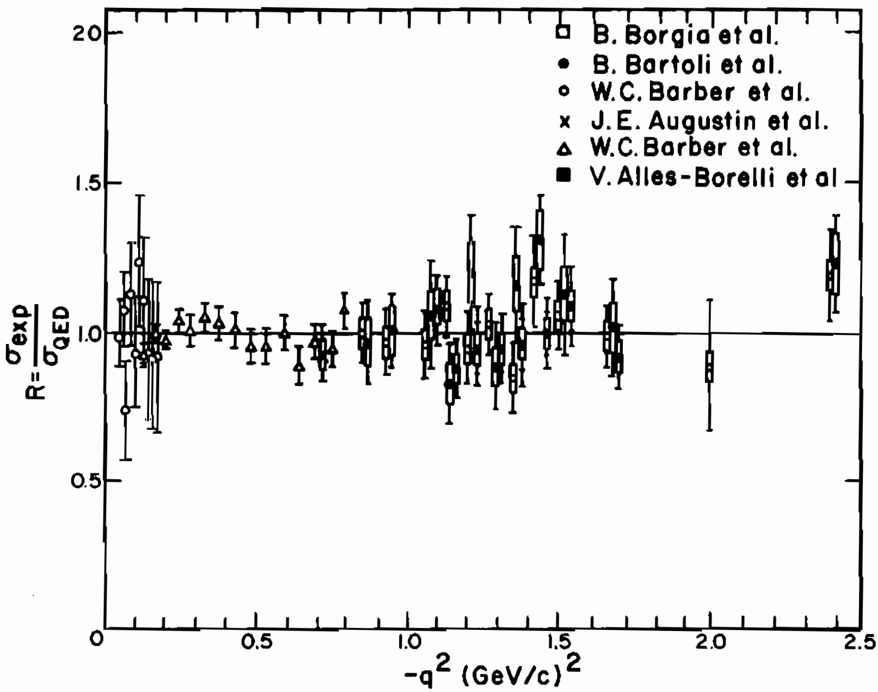


Fig. 2. Experimental results on elastic e^+e^- and e^-e^- scattering, expressed in terms of the ratio $R = \sigma_{exp}/\sigma_{QED}$.

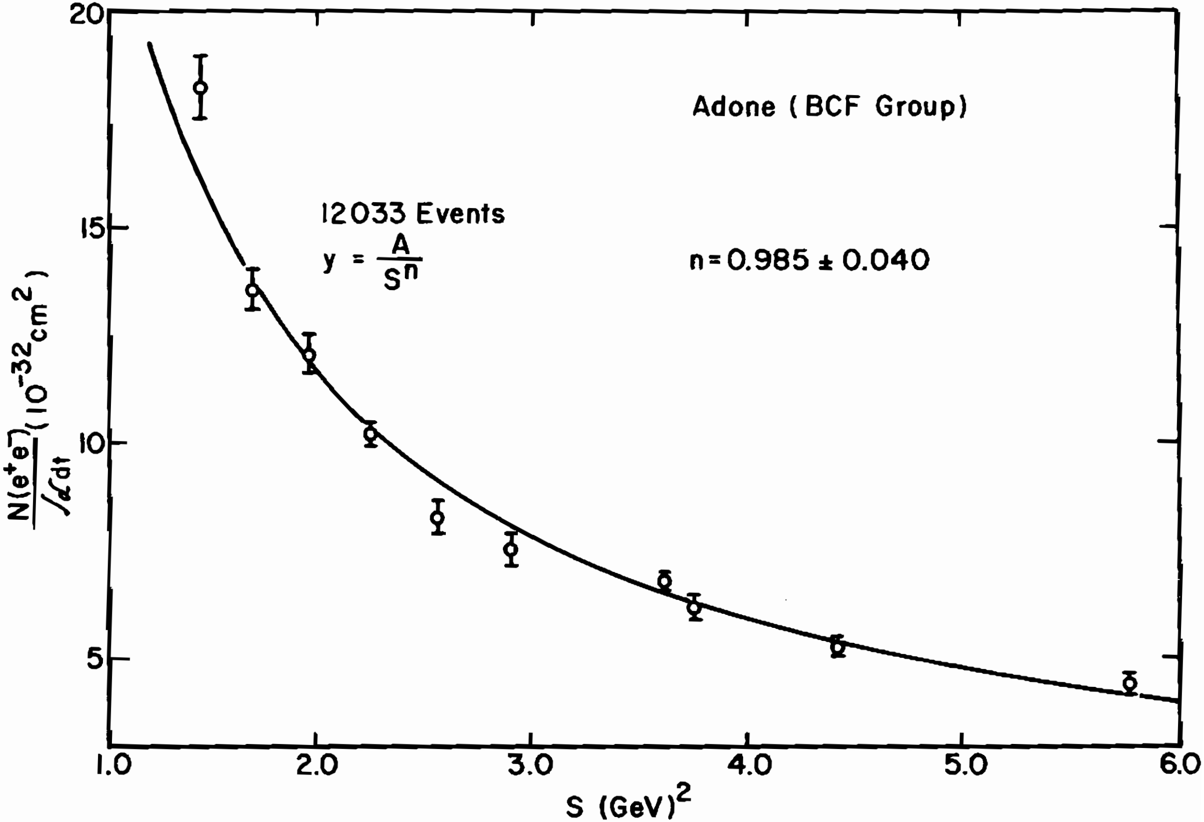


Fig. 3. Experimental results on reaction $e^+e^- \to e^+e^-$ presented at this conference by the BCF group working at Adone (Ref. 14). The results are expressed in terms of yield per unit luminosity and are compared with the predictions of QED.

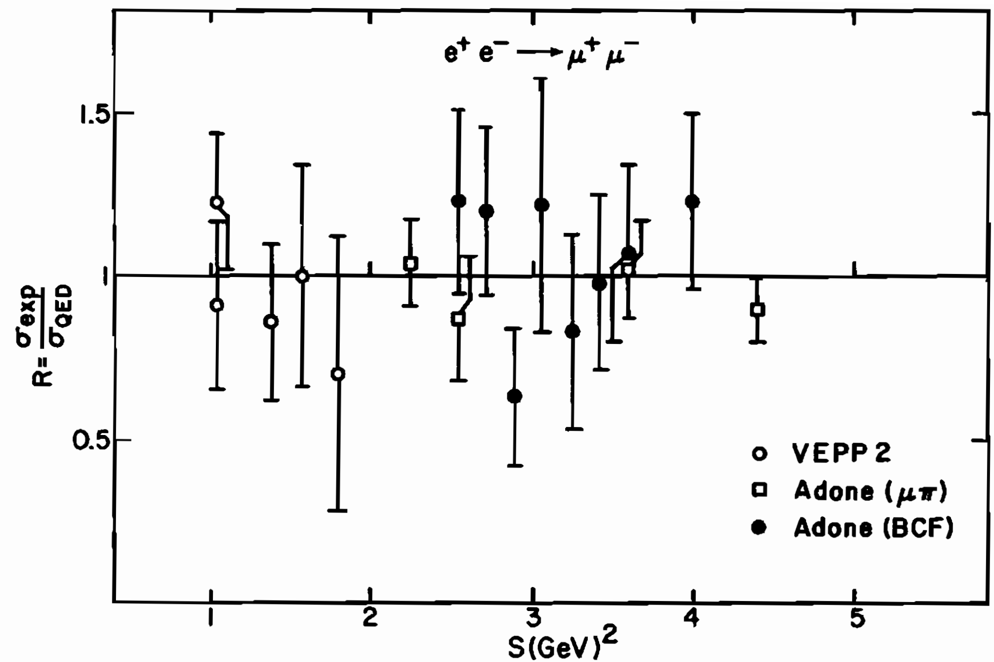


Fig. 4. Experimental results on reaction $e^+e^- \rightarrow \mu^+\mu^-$, expressed in terms of the ratio $\sigma_{exp}/\sigma_{QED}$.

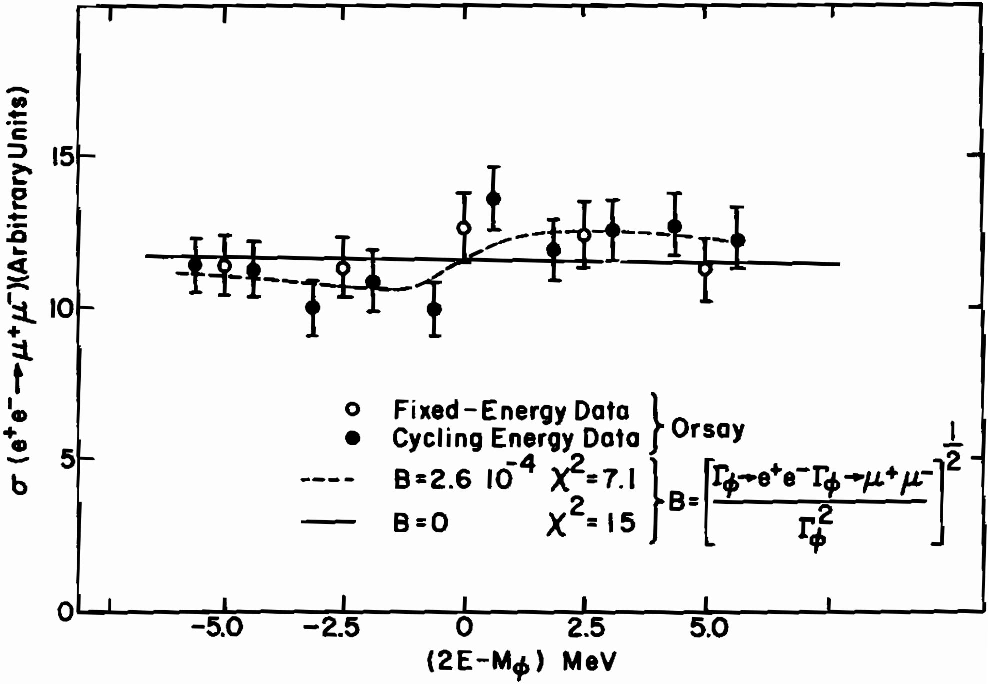


Fig. 5. The results of the Orsay group on reaction $e^+e^- \to \mu^+\mu^-$ at a total energy around the ϕ mass. The abscissa is the difference between the total energy 2E and the mass of the ϕ m_ϕ (MeV).

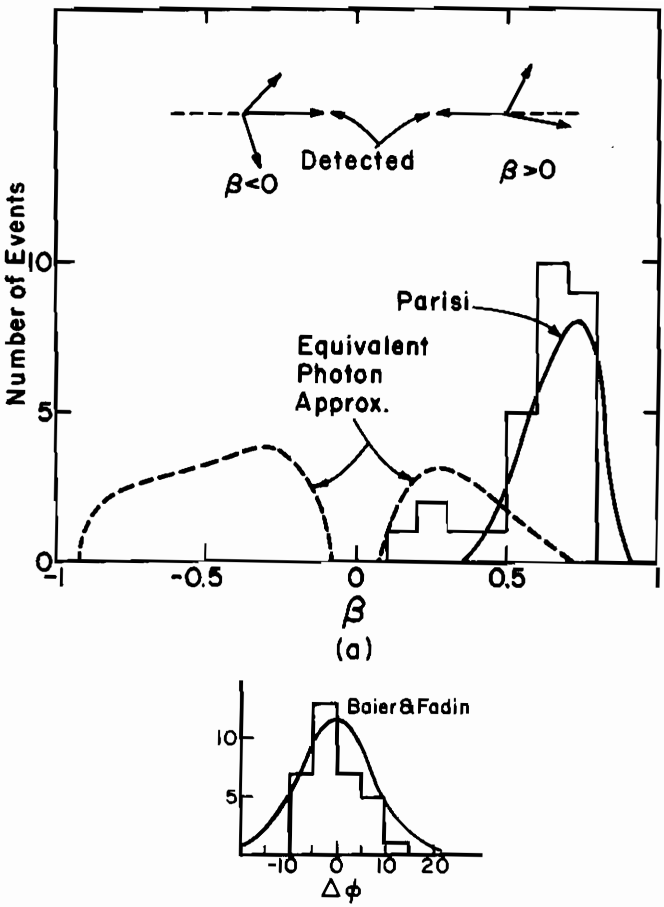


Fig. 6. The results of the Frascati γγ-group on the reaction $e^+e^- \rightarrow e^+e^-e^+e^-$. This histogram of Fig. 5(a) represents the number of events as a function of β, the center-of-mass velocity of the two leptons emitted at large angle. The sign of β is defined with respect to the third lepton detected at small angle, as shown in the upper part of Fig. 5(a). Figure 5(b) shows the distribution of the events as a function of the noncoplanarity angle $\Delta\phi$ between the two leptons emitted at large angle. The theoretical calculations are performed according to Refs. 23 and 26.

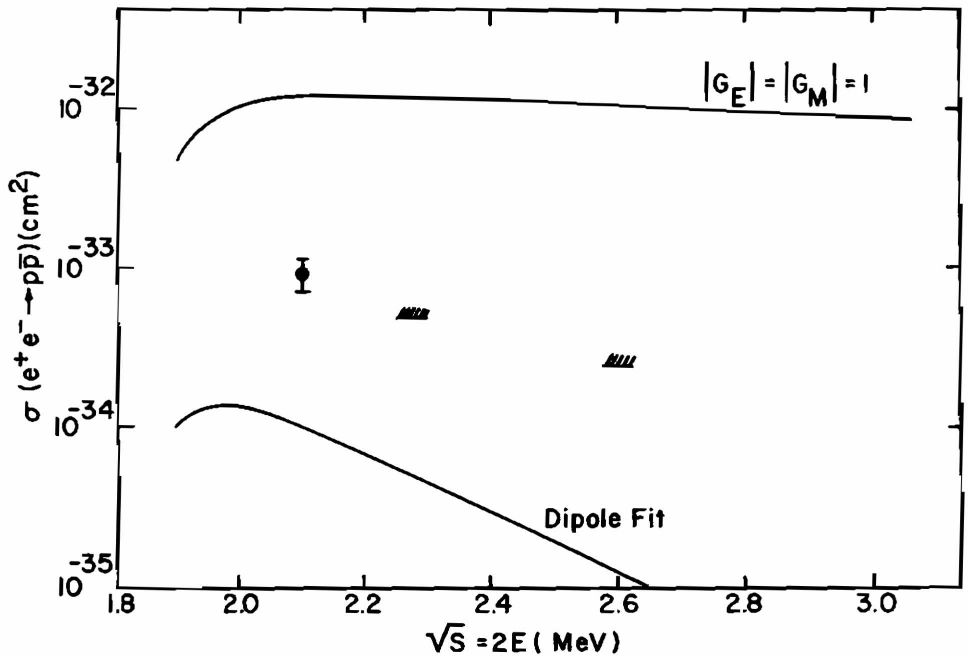


Fig 7. The cross section for process $e^+e^- \rightarrow p\bar{p}$ as obtained by the Naples group. Previously available upper limits from the reaction $p\bar{p} \rightarrow e^+e^-$ are also displayed. For reference, the curves corresponding to two naive theoretical predictions are also shown.

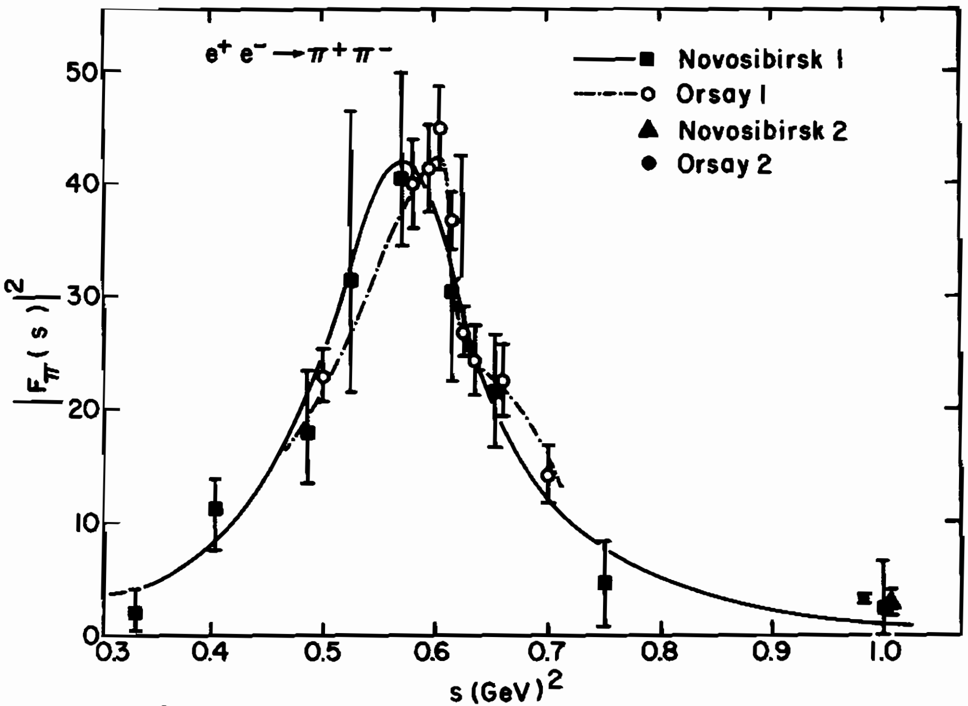


Fig. 8. $|F_\pi(s)|^2$ as determined by the Novosibirsk and Orsay groups through measurements of the reaction $e^+e^- \rightarrow \pi^+\pi^-$ at $S \leq 1\ \mathrm{GeV}/c^2$. The full-line is the Breit-Wigner best fit to the Novosibirsk points. The dash-dotted line is the best fit to the Orsay points using a Gounaris-Sakurai formula and taking into account the ω contribution via the decay channel $\omega \rightarrow \pi^+\pi^-$.

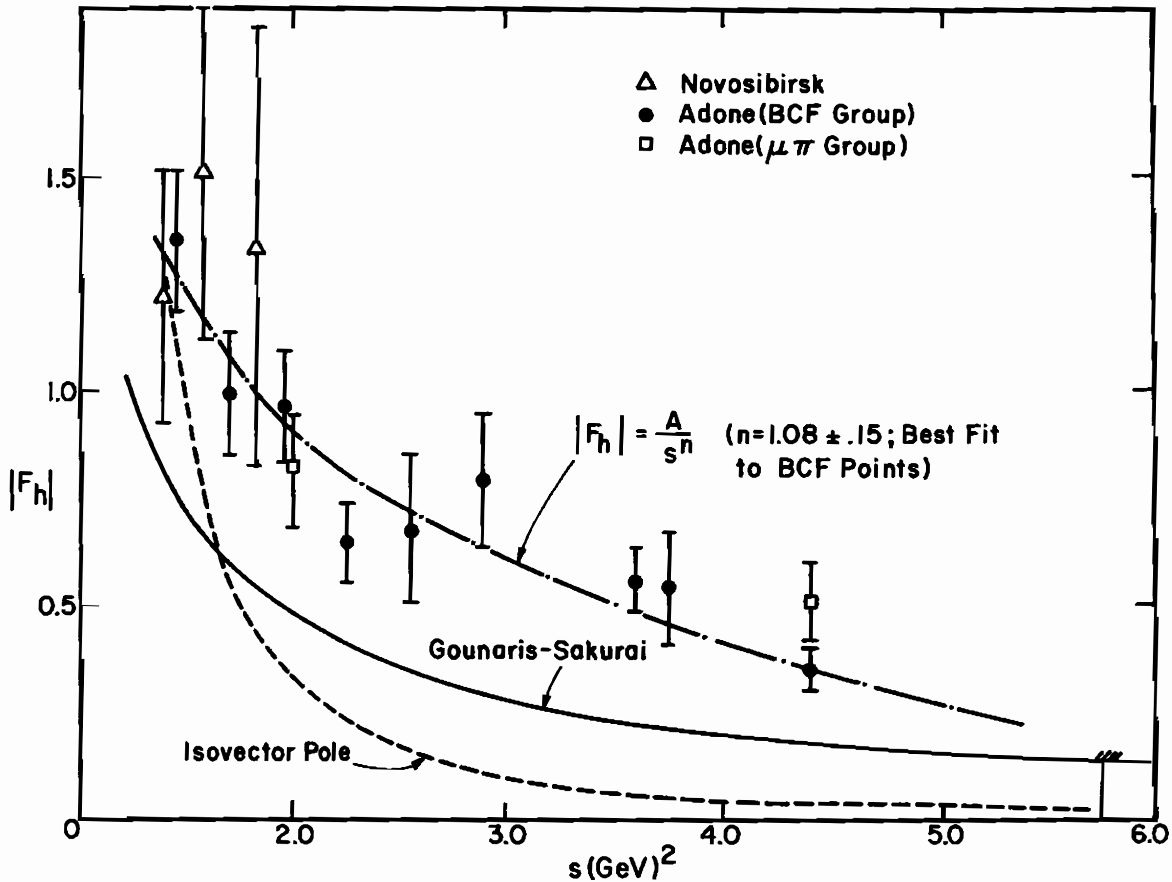


Fig. 9. $|F_\pi(s)|$ as determined by measurements of the reaction $e^+e^- \to \pi^+\pi^-$ at $s \geq 1$ (GeV)^2. The expected contribution from the e-tail is shown. Corrections for a possible contamination of kaons in the sample of pions are not applied in the Frascati points.

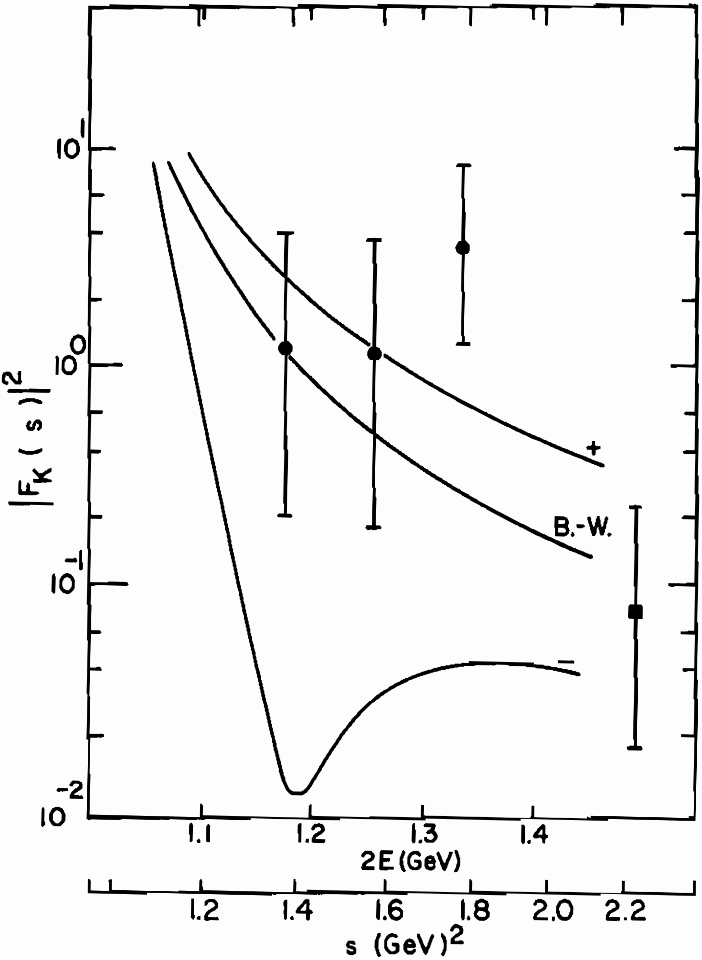


Fig. 10. $|F_K(s)|^2$ as determined by measurements of the reaction $e^+e^- \to K^+K^-$ at $s \gtrsim 1\ GeV^2$. The meaning of the curves is explained in the text.

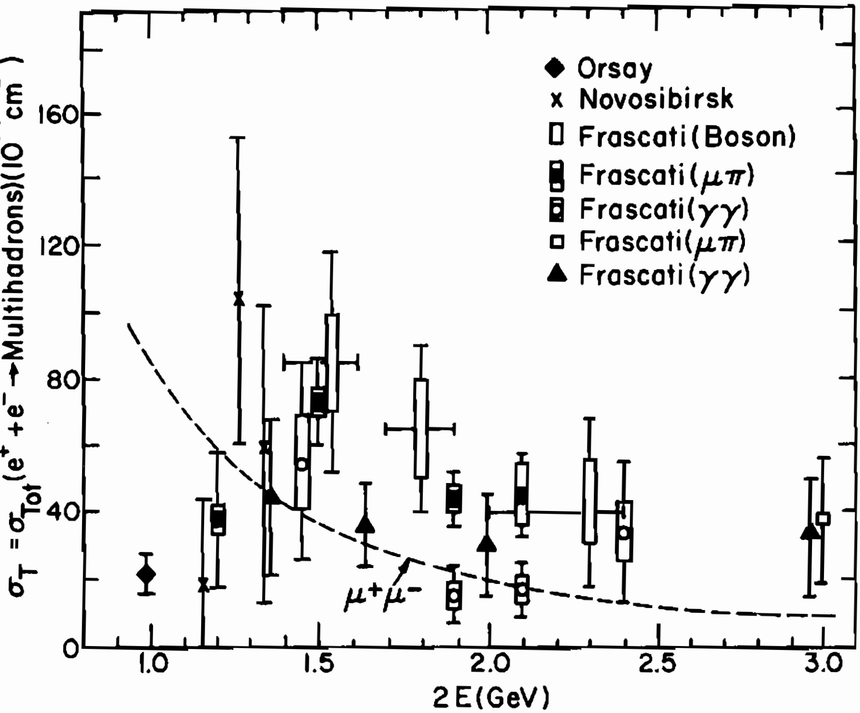


Fig. 11. $\sigma_{total}(e^+e^- \rightarrow \text{multihadron})$ as a function of the total energy $2E = E^+ + E^-$ up to $2E = 3$ GeV. ◆ : Ref. 47; X : Ref. 32; ▯ : Ref. 46; ▮ : Ref. 48; ▣ : Ref. 42; □ : Ref. 49; ▲ : Ref. 50.

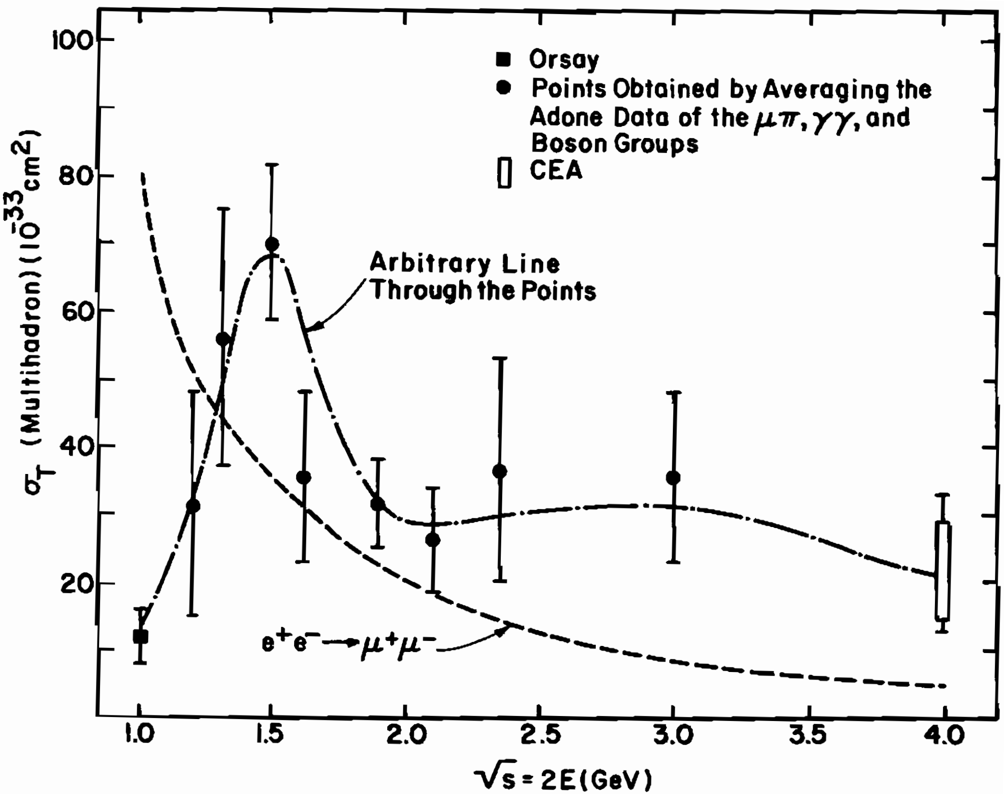


Fig. 12. $\sigma_T(e^+e^- \rightarrow$ multihadron) as a function of the total energy, as obtained by properly grouping and averaging the points of Fig. 11. The total energy extends now up to 4 GeV, where we have the new CEA point.

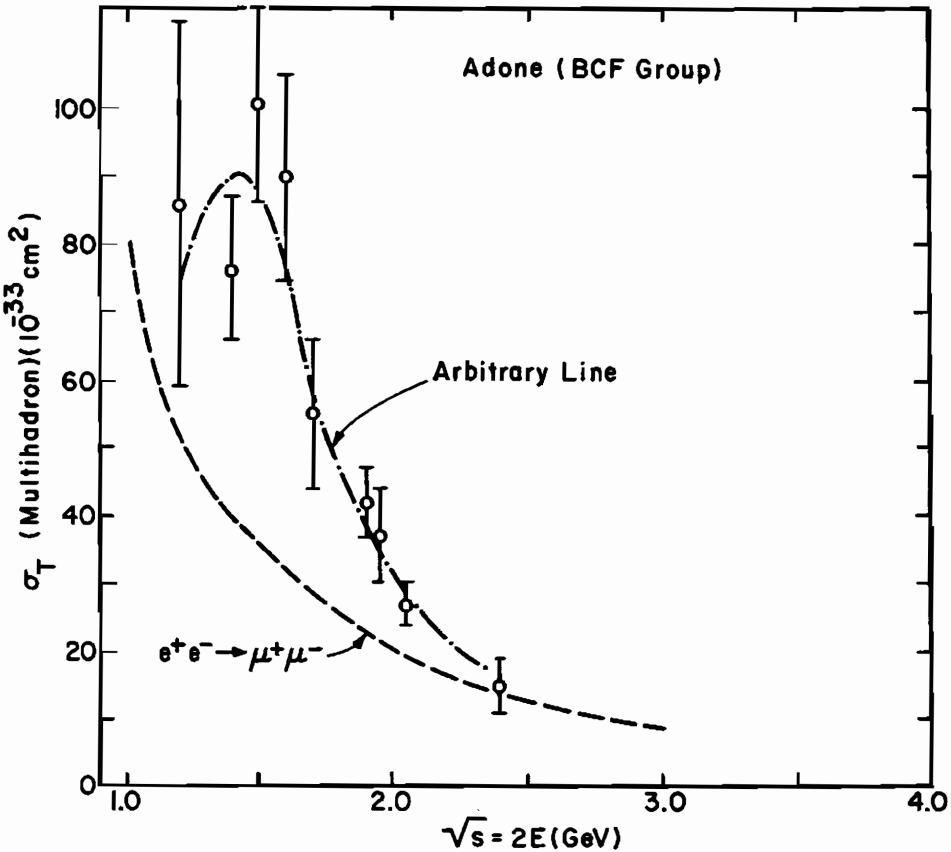


Fig. 13. $\sigma_T(e^+e^- \rightarrow$ multihadron) as a function of the total energy (BCF group). These results have been obtained by assuming the same multiplicity distribution as in $p\bar{p}$ annihilation.

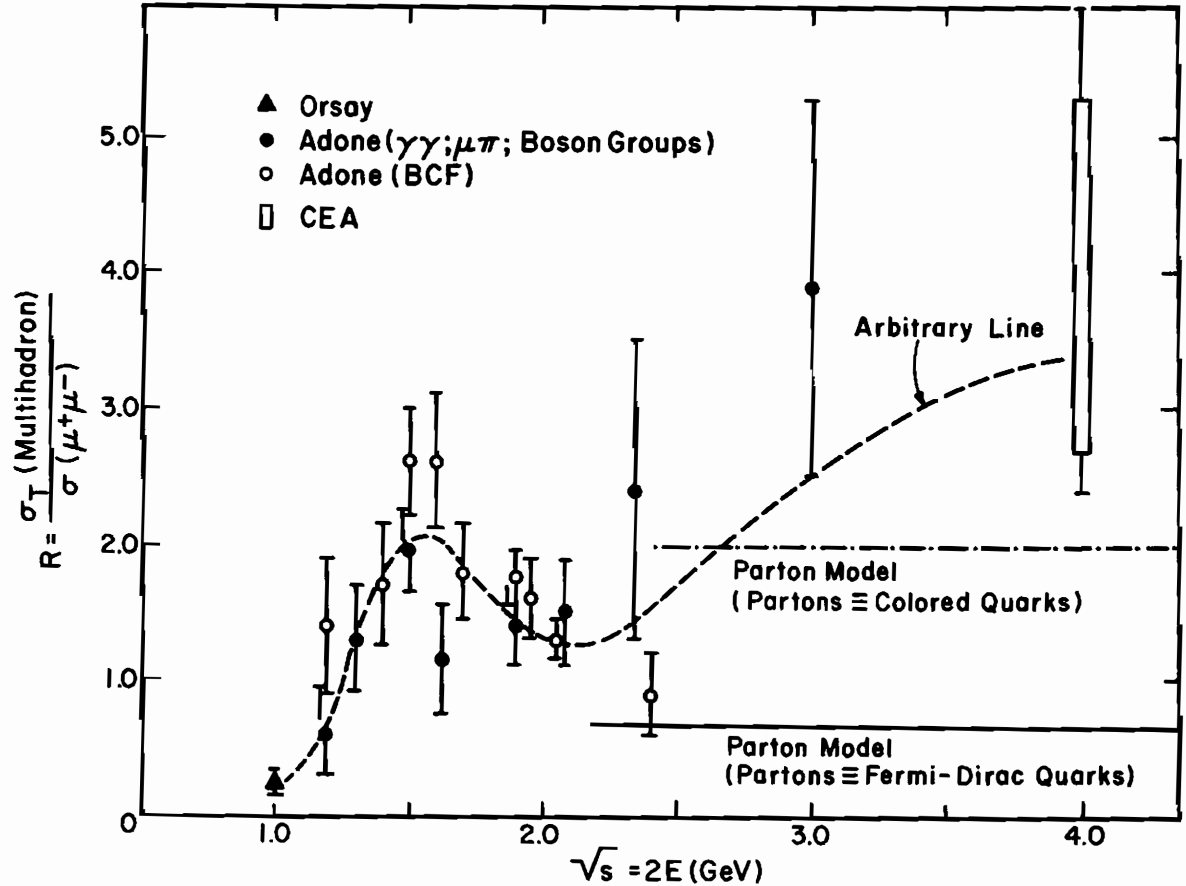


Fig. 14. $\sigma_T(e^+e^- \rightarrow \text{multihadron})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ as a function of the total energy.

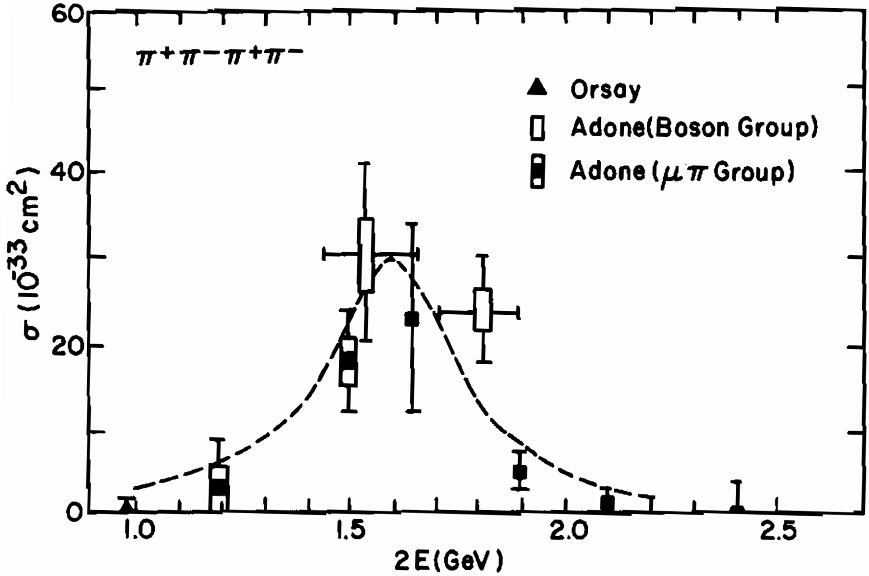


Fig. 15. $\sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-)$ as a function of the total energy 2E. ▲ : Ref. 47; ▯ : Ref. 46; ▮ : Ref. 48.

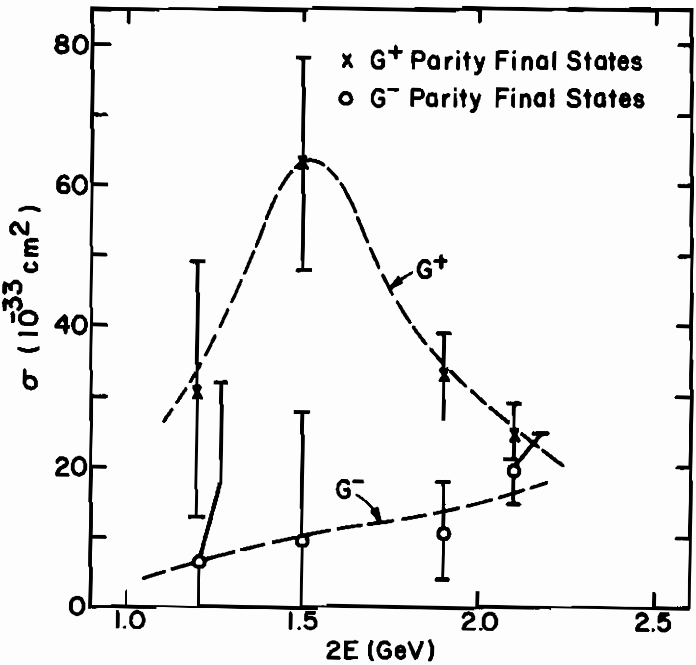


Fig. 16. σ_{G^+} and σ_{G^-}--the cross sections to produce an even and an odd number of pions--as a function of energy (Ref. 48).

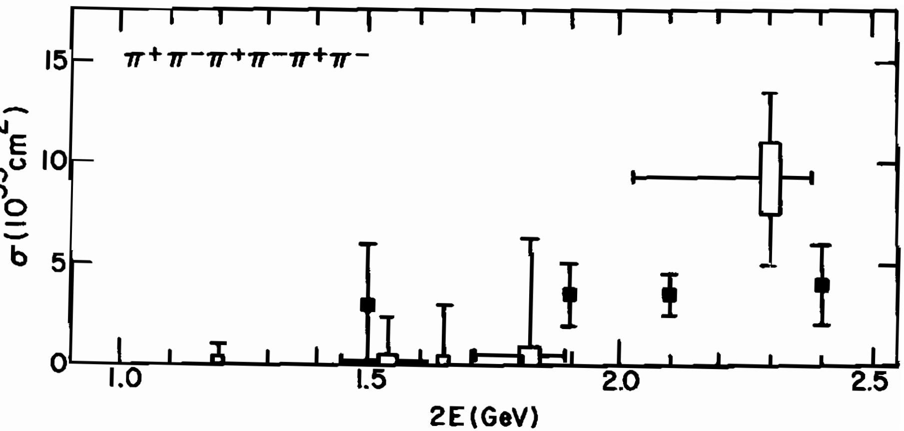


Fig. 17. $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-)$ as a function of energy. ▯ : Ref. 46; ■ : Ref. 48.

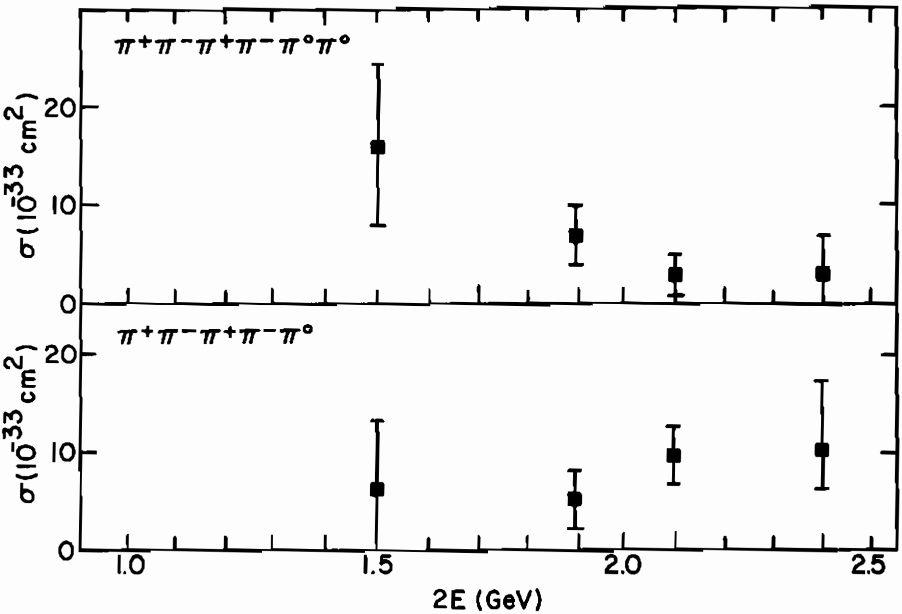
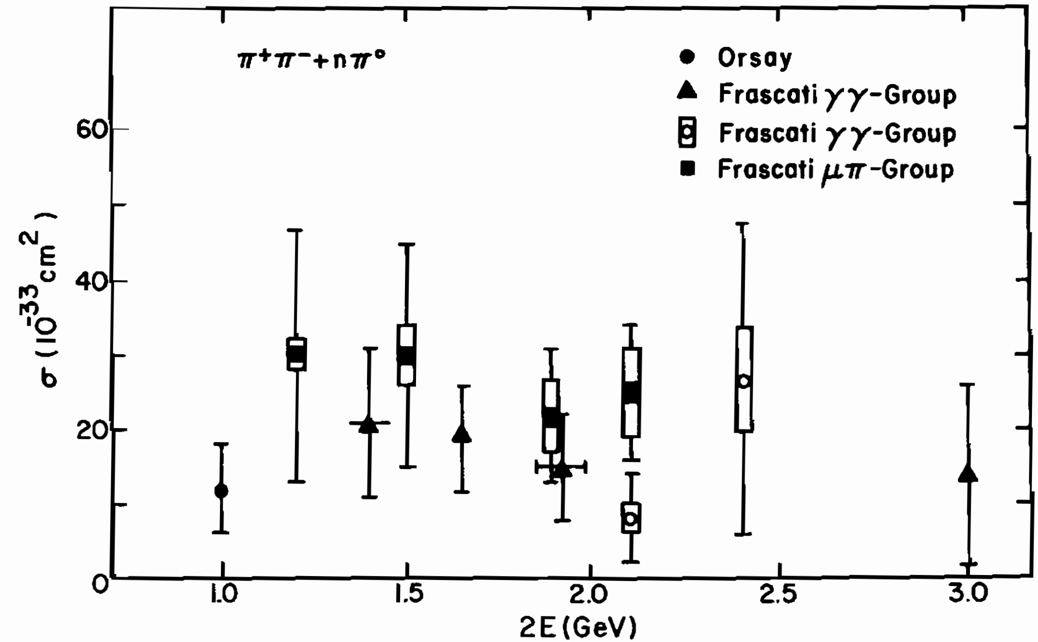


Fig. 18. $\sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0)$ and $\sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0)$ as a function of energy (Ref. 48).



Ref. 19. $\sigma(e^+e^- \rightarrow \pi^+\pi^- + n\pi^0)$ as a function of energy. ● : Ref. 47; ▮ : Ref. 48; ▯ : Ref. 42; ▲ : Ref. 50.

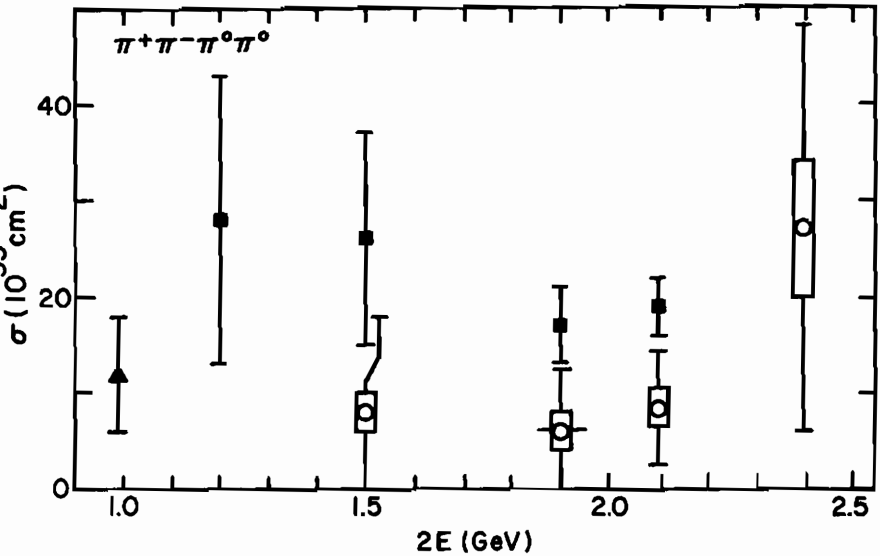


Fig. 20. $\sigma(e^+e^- \to \pi^+\pi^-\pi^0\pi^0)$ as a function of energy. ▲ : Ref. 47; ▯ : Ref. 42; ■ : Ref. 48.

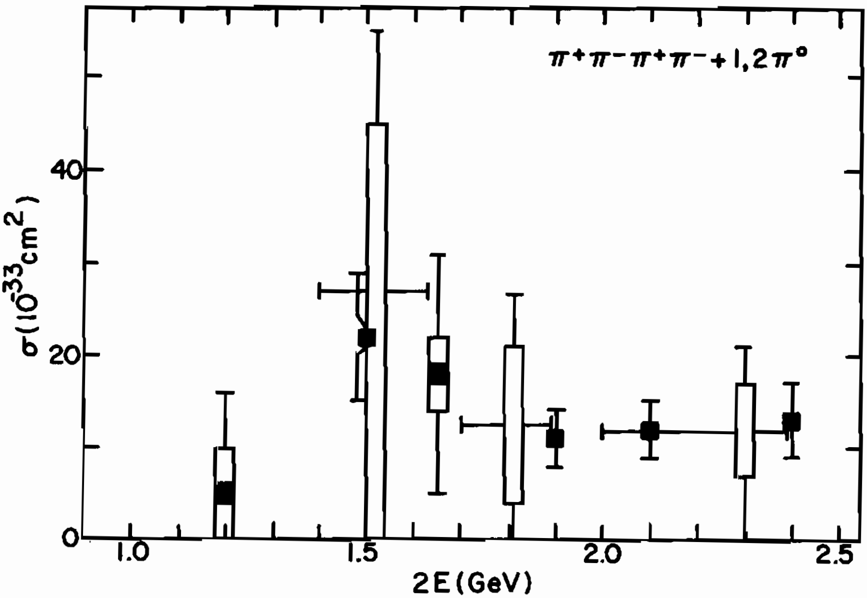


Fig. 21. $\sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^- + 1, 2\pi^0)$ as a function of energy. (Same notations as in Fig. 17.)

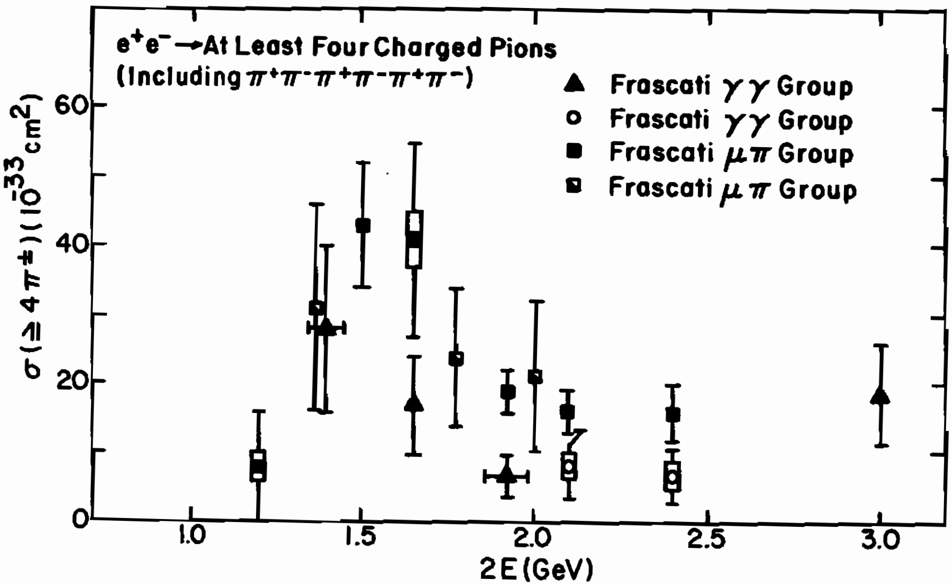


Fig. 22. $\sigma(e^+e^- \rightarrow$ at least 4 charged pions) as a function of energy. ▲ : Ref. 50; ◻ : Ref. 42; ■ : Ref. 48; ◪ : Ref. 58.

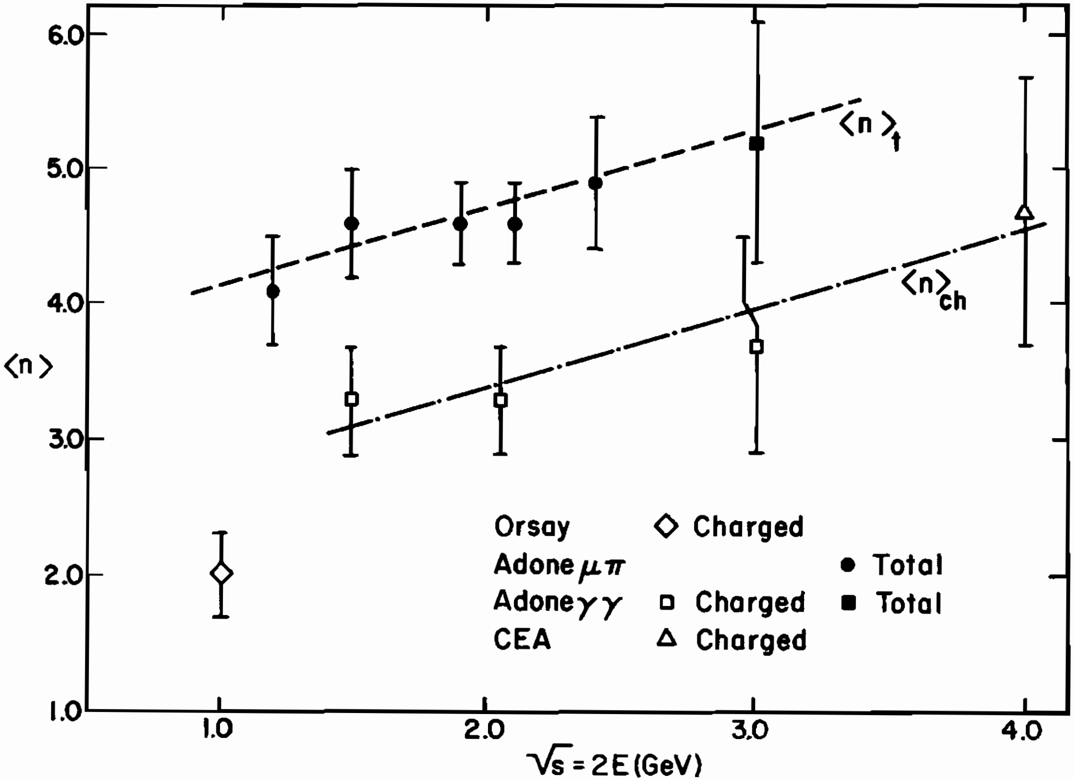


Fig. 23. The average charged and total multiplicity in multihadron production as a function of the total energy.

DISCUSSION

R. W. Williams (Washington): In discussing the e^+e^- elastic scattering and going into $\mu^+\mu^-$ you killed en passant the famous old idea of a cutoff in QED. Since this always used to be one of our most famous numbers at these meetings perhaps it deserves, if not a eulogy, at least a decent burial. Do you really mean to say that the virtual presence of strong interactions renders the concept totally useless?

V. Silvestrini: I wanted to say a few words about that. I don't think the cutoff parameter is very useful. After all, it was introduced in order to interpret the data in terms of an upper limit on a radius. But we know that at high energies this Fourier interpretation of the form factor is not valid; so why to use it. It is usually introduced to compare different experiments or different experimentalists among themselves. We don't need that, we only need to compare theory with experiment. The best parameters are the precision of the experiment and the values of the momentum transfers. Tell us what the results of the experiment are and that is all. I do not want cutoff parameters.

E. A. Paschos (NAL): Did you look for a polarization in the stored electron-positron beams at Adone?

V. Silvestrini: No, we did not.

E. Paschos: Is there a measurement from Orsay?

V. Silvestrini: There is a measurement from Orsay, but I am afraid I am not very familiar with it. I know our values of the cross sections are not very sensitive to the polarization. Maybe somebody from Orsay can make a comment. They found a polarization of about 10 per cent with large errors, compatible with the calculations.

J. Buon (Orsay): It is true we have seen a polarization which is compatible with the Novosibirsk calculations in that case. This measurement was performed with only one beam in the machine. Then there is a question: Is there any polarization with two beams inside the machine, and interacting? Just now there is a preliminary result which shows that there is some polarization with two beams stored in the machine. Perhaps we have an indication that the polarization decreases with the intensity of the two beams, due to the beam-beam interactions.

A. Zichichi (Bologna): I would like to make a few remarks; the first concerns the checks of QED. As it is well known the total cross section for $e^+e^- \to e^+e^-$ depends from the space-like amplitude as well as from the time-like one and from their product (the interference term). The space-like one is more important but it is not the only one. Therefore to say that we check only the space-like part, with our ~12,000 $e^+e^- \to e^+e^-$ events, is not very appropriate. Furthermore, even if this were perfectly true (only space-like q^2 investigated), the values of s have been spanned from 1.45 up to 5.8 GeV^2, and this is the first time that QED cross sections are checked to have within 4 per cent the expected s dependence.

The second remark refers to the range of $F^h(q^2)$ which goes up to 5.8 GeV^2 (it does not end at 4.4 GeV^2). Let me take this occasion to make clear the relevance of our results: the meson and the nucleon isovector electromagnetic form factors are different.

Finally, let me mention that we have also tried the Renard predictions for the hadronic final-state multiplicity in e^+e^- annihilation, and the behavior of the total cross section $\sigma(e^+e^- \to \text{hadrons})$ remains almost unchanged.

V. Silvestrini: I am sorry, but I disagree with your second remark. At the highest energy you have in fact only an upper limit.

A. Zichichi: This upper limit, however, plays an important role.

S. C. C. Ting (DESY/MIT): You mentioned the precise check of QED by the Frascati-Bologna group. You also mentioned that radiative corrections were taken into account and have been measured experimentally. What is the size of radiation correction, and how was it done?

V. Silvestrini: The radiative corrections due to the emission of hard photons have been measured by the BCF group by measuring the acoplanarity distribution in reaction $e^+e^- \rightarrow e^+e^-$.

A. Zichichi: Concerning radiative corrections, we have used the exact form integrated over the acceptance, but when we quote an absolute value, we mean absolute value including first-order radiative corrections. Furthermore, we have proven that the peaking approximation is not a good enough approximation because we have by now a few hundred e^+e^- pairs with larger coplanarities of the order of $10°$-$20°$-$30°$. We measure in our setup that the amount of deviation from peaking approximation is 3 ± 0.8 per cent, and this agrees well with the measured acoplanarity distribution. The most recent theoretical work was done by Capateli, Kessler, and Parisi in France.

A. V. Efremov (Dubna): Could you comment on the result of the Parisi calculation of $e^+e^- \rightarrow e^+e^-e^+e^-$? Is the calculation the result of some approximation?

V. Silvestrini: Yes, it is. In all the story there is no indication of deviations from QED. It is only a question of approximations in the calculations.

G. Salvini (Rome): As we have seen, the multiplicity of the produced hadrons as a function of the energy changes rather smoothly from 2 to 4 GeV. However, I must underline that we have some evidence that the rate of different events may be rather different from one energy to the other. For instance, the reaction, $e^+e^- \rightarrow \pi^+\pi^-\pi^0$, seems to increase rather than decrease with energy, and this is a low multiplicity channel. In general I would say that, notwithstanding the nice appearance of the multiplicity curve, we could still be far from the asymptotic region. In this case, it would not be possible yet to extrapolate from our results at 3 and 4 GeV the total cross section for hadronic production at higher energies.

S. J. Brodsky (SLAC): In regards to the eeee final states measured, the calculation of our group, that is Brodsky, Kinoshita, and Terazawa, does not apply, of course, to this situation. The calculation is not valid in this configuration and the calculation should not be applied. In fact we only considered the case $s_{min} >> m_e^2$.