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SUMMARY OF e^+e^- COLLIDING BEAM EXPERIMENTS*

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ABSTRACT

This paper discusses recent experiments related to $e^+e^- \rightarrow$ hadrons. Subjects discussed include hadron form factors, the total hadronic cross section, multiplicities and some specific channels.

INTRODUCTION

The field of e^+e^- colliding beams has grown enormously in the past five years. In 1968 the total number of papers related to such experiments was just a handfull, and every interested physicist could very easily bring himself up to date on all developments in e^+e^- colliding beam physics in an afternoon's reading. Today for someone already immersed in the field it is necessary to launch a major literature search to present a coherent set of timely information. Even then he will be obliged to select the areas of special interest to him. Even though there are about 10 theoretical papers published for every experimental paper in the field I shall concentrate heavily on the experimental issues. Thus it is that in delivering my summary I have selected only those areas of this branch of physics which I find most interesting, and that certain areas will be neglected. I deliberately choose to develop a selected set of topics to the neglect of others just to present a coherent picture of the controversial experimental issues at this time. Almost the entire discussion will be devoted to hadron physics in the single photon annihilation channel. There will be no discussion of tests of Quantum Electrodynamics.

Experiments with e^+e^- storage rings are not particularly easy, in large part because of the low data rates which are generally available. At the risk of boring some members of the audience I shall indicate what makes the investment of effort worthwhile. First, an annihilation process is the cleanest method of obtaining information on the behavior of time-like photons. This fact opens a whole new area to studies of form factors. Secondly, the single photon annihilation process is a means of preparing a pure $J^{PC} = 1^{--}$ initial state of fixed energy and momentum. Rarely does a hadron physicist have the luxury of such a state of well defined quantum numbers. In addition to the purity of the state, its richness is somewhat overwhelming, because any particles which even indirectly couple to a photon may be produced. Nevertheless, there are limitations; for example any final state consisting entirely of π^0's cannot be produced because such a state has even charge conjugation. There is no way to investigate $c = +1$ states with a single photon initial state. It has been pointed out, however, that a two photon initial state can be prepared with colliding beams; such a state would have $c = +1$ but lacks a definite angular momentum, energy, or momentum. The branch of two photon physics has been much admired and discussed, but mainly as a novelty. Unfortunately because of its novelty it has been subjected to a great

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excess of calculation per unit thought by theoreticians and experimentalists alike. There is much room for creative work in the physics connected to the two photons rather than the QED or approximations thereto to calculate the equivalent photon fluxes.

FORM FACTORS

Since the early days of high energy physics people have studied electromagnetic form factors, and by now very extensive studies have been made in the space-like region. With few exceptions the other half of the world, the time like region, was inaccessible. Historically the first study of form factors was for nucleons and only with much difficulty and through indirect means were any meson form factors studied. For several reasons this order was reversed when the time like region became accessible. The pion form factor was studied first in some elegant but difficult experiments at Orsay[1,2] and Novosibirsk.[3] The strong coupling of the two pions to the ρ, which, being a 1^{--} state, has the same quantum numbers as a photon. Thus there was a spectacular peak in the pion form factor, as shown in Fig. 1. The same experiment[2] allowed a study of ρ-ω interference via the G-parity violating amplitude $\omega \to \pi^+\pi^-$. A dramatic peak in the K form factor[4,5] is a reflection of the existence of the ϕ vector meson; see Fig. 2. However, away from these well known vector mesons no dramatic structure has been found in the pion form factor. Figure 3 shows a compilation of existing data[2,6-8] on the pion form factor for $s \geq 1$ GeV^2. The figure does not show all the world's data; a few datum points having very large estimated errors have been discarded in the interest of a tidy picture. The fall off of the square of the form factor is consistent with s^{-2}. This smooth fall is a disappointment to those who would seek another vector meson coupling to $\pi^+\pi^-$. The rate of fall is also somewhat disappointing to people planning such measurements at higher energies. If this rate continues to $s = 27$ GeV^2, the highest energy available at SPEAR, this process will be all but lost in the noise. Nevertheless, one must look and perhaps there could be a surprise. A word of caution should be injected here about this figure. The data for

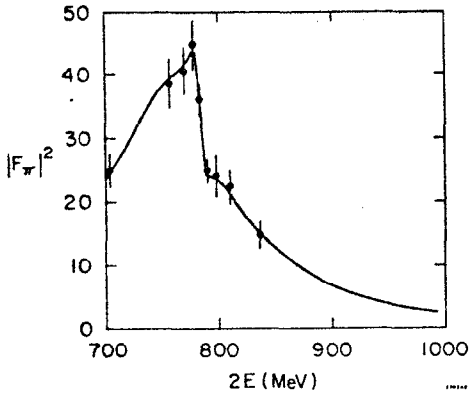

FIG. 1--Measurements of pion form factors in the region of the ρ (Ref. 2).

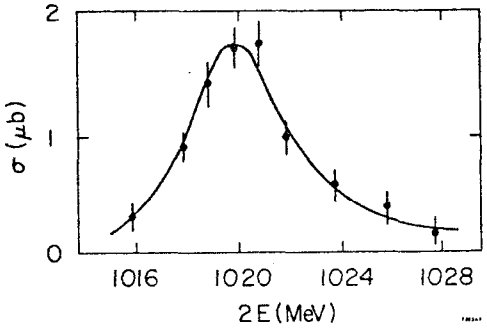

FIG. 2--Representative measurements of kaon form factors in the region of the ϕ (Ref. 5).

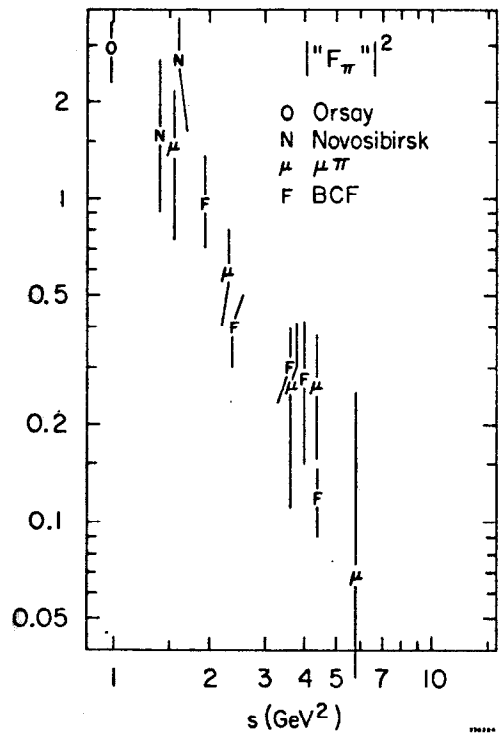

FIG. 3--Measurements of pion form factor at high energies. Data selected from Refs. 2, 6-8.

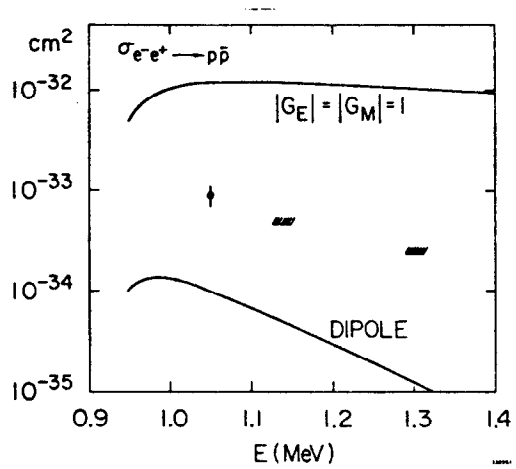

FIG. 4--Total cross section for $e^+e^- \to p\bar{p}$ (Ref. 9) compared with upper limits obtained for $p\bar{p} \to e^+e^-$ by Refs. 10 and 11.

$s < 2.25$ GeV^2 are unambiguously identified as being pionic events. Above this region the situation is not so clear, since no compelling separation of pions from kaons has been made. Simplest arguments based on SU_3 would indicate that the number of K's should be the same as the number of π's. A perhaps more realistic scheme of SU_3 breaking would have the number of K's only one third the number of π's. Experimentally the situation is somewhat murky; the BCF group[8] has presented some data indicating that perhaps half of their data for $2.25 \leq s \leq 2.9$ GeV^2 may be due to kaons. If such be the case then Fig. 3 only gives a crude upper bound for $|F_\pi|^2$. Personally I do not find the BCF evidence for the K rate compelling.

Direct measurements of the K form factor away from the ϕ meson are only order of magnitude results[6] in the neighborhood of 1 for $s \sim 1.6$ GeV^2. This will probably remain a tough nut to crack if the K form factor continues to fall at the same rate as the pion form factor.

The measurement of the nucleon form factor in the time like region has had to wait for some rather recent results from Frascati-Naples.[9] Figure 4 shows the result of their measurement, $\sigma(e^+e^- \to p\bar{p}) = 0.91 \pm 0.22$ nb. This measurement is shown along with some upper limits set by searches[10,11] for $p\bar{p}$ annihilations into e^+e^-. As can be seen the measurement lies between the optimistic and pessimistic estimates of the cross section. Unfortunately for the world of physics the region of the vector mesons is kinematically inaccessible to this reaction. Thus it is not possible to do the analog of the π form factor in the region of interest.

MULTIHADRON PRODUCTION

The study of multihadron production has produced great stimulation to theoretical thought on parton or quark models. The cross sections turned out to be remarkably large and none of the first generation experiments were properly instrumented to handle the process. Nevertheless people went ahead and did the best they could with the data. Figure 5 shows a compilation of the world's data[12-17] on the total cross section for producing multihadrons. It should be emphasized that the commonly used description of total cross section is somewhat of a misnomer. What is meant here is a final state having at least two charged hadrons plus something else. This figure shows the ratio of σ_{tot} to the cross section for producing a pair of massless, ideal Dirac particles, generically called $\sigma_{\mu\mu}$. This ratio is useful first because it removes some expeced kinematic factors, and second it emphasizes the magnitude of the cross section; thirdly note the dramatic difference of character from the s dependence of the pion form factor squared (which is $\simeq 4\sigma_{\pi\pi}/\sigma_{\mu\mu}$). The ratio $\sigma_{tot}/\sigma_{\mu\mu}$ is at worst a constant with s and more likely is increasing. G. Tarnopolsky has reported to this conference the latest result from CEA at $s = 25\ GeV^2$; $\sigma_{tot}/\sigma_{\mu\mu} = 5.4 \pm 1.3(\pm 0.6)$. Such a large cross section gives much trouble to quark model builders, who say that $R = \sigma_{tot}/\sigma_{\mu\mu} = \sum_i Q_i^2$, where Q_i are to the charges of the constituents. The idea is that a pair of quarks are produced and they dress themselves as multihadrons. The model is simple and thus appealing. Unfortunately "old fashioned" quarks predict that R = 2/3, which lies far below the data. The suggestion of introducing three different kinds of quarks having color allows one to triple R. This is a big help and such a result would satisfy all the Frascati data, but is inconsistent with both the CEA points a higher s. There are other variations, for example adding charm, which allows R = 10/3. Frankly I find such maneuvering rather unconvincing. The idea is attractive, but one must be honest too and recognize the weakness of extreme simplicity, where all but the most rudimentary kinematics have been discarded. There is no compelling reason to believe that we have reached the asymptotic region where we can afford such luxuries. There is, for example, no prohibition against the ratio peaking and then falling. In fact if one looked only at the data below $s = 9\ GeV^2$ this is a consistent statement. A large part of these data are

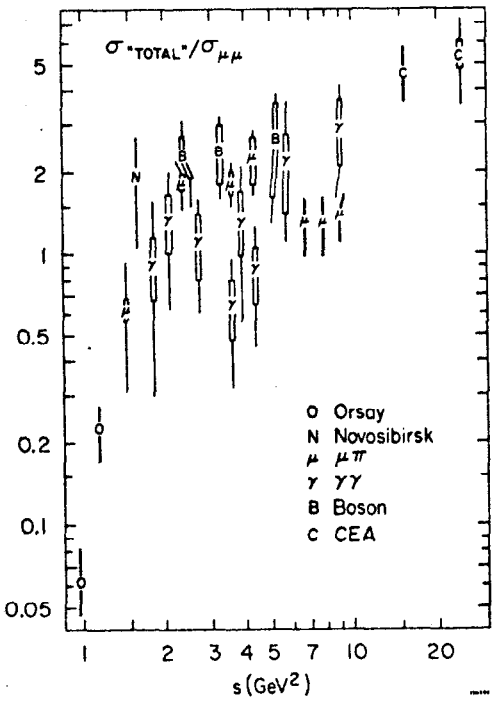

FIG. 5--Measurements of "total" hadronic annihilation cross section divided by point-like pair cross section. Data derived from Ref. 12-17. Note, the data from Ref. 12 represent only $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ data.

represented by what has been advertized as the ρ', which is certainly not part of an asymptotic region. This should raise a feeling of caution to the model builders: these experiments are hard, and not all experiments agree on the results. For example, the points by the $\gamma\gamma$ group at Frascati are consistently lower than the other two Frascati groups represented by published or preprint data. In addition all experiments must make rather large corrections for detection efficiency. To a greater or lesser extent all of these results are dependent upon the models used to calculate these efficiencies. Generally a pure phase space model has been used, and various models have been used to test sensitivity to the choice of model. As a defense against this problem both the CEA points have also been stated as lower bounds defined by assuming unit efficiency. This lower bound is roughly half their best estimate for the ratio R. Since this is a very extreme case one must take seriously the fact that $R \gtrsim 2$ unless there is some unknown background.

Also of interest to model builders is the observed average multiplicity[17,18] shown on Fig. 6. Plotted here are both the average charged multiplicity as well as the estimated total multiplicity. A new entry at s = 25 to

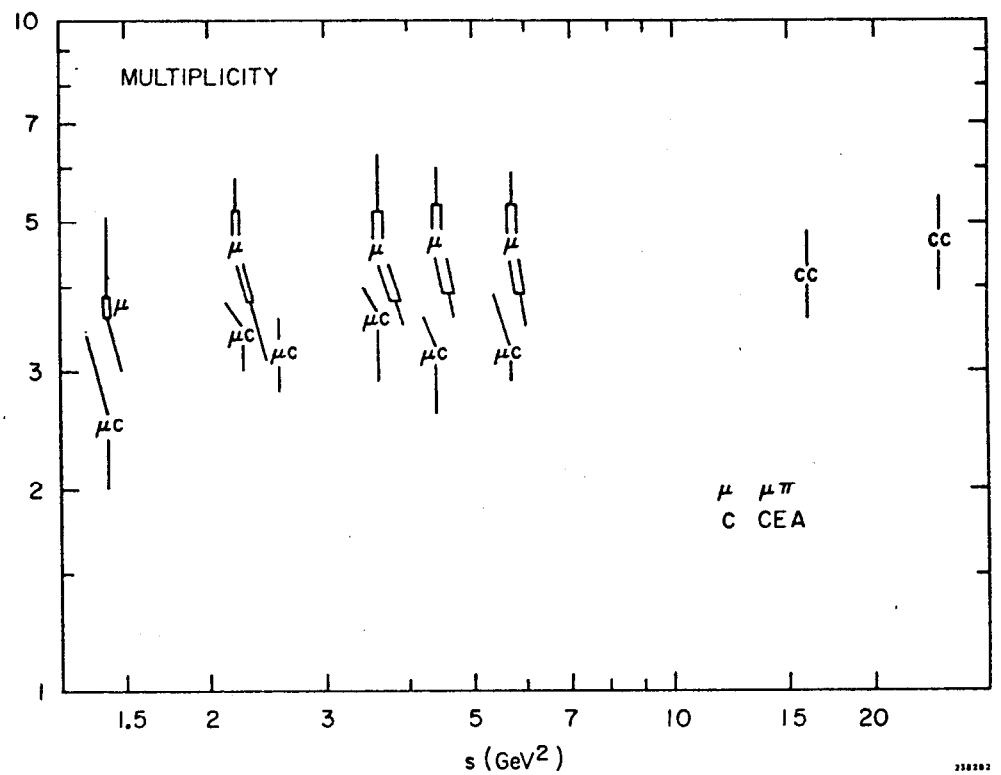

FIG. 6--Average charged and total multiplicity for multihadron production. Data from Ref. 17, 18. Charged multiplicity points have a "c" appended to the experiment legend.

this plot has been reported by CEA at this conference. It is clear that the total multiplicity exceeds the charged multiplicity by about one and that both multiplicities vary only slowly with s. A simple statistical model[19] of energy limiting would lead one to expect $\langle n \rangle \sim \sqrt{s}/\langle E_\pi \rangle$. Other models would predict a logarithmic increase similar to that observed in ordinary hadronic reactions. The existing data do not clearly distinguish between the two alternatives if an arbitrary additative constant is allowed.

One of the clear predictions of quark models of multihadron production is the appearance of jets of hadrons along the path of the pair produced quark. Unfortunately at present no such jets have been found, but none are really expected at the energies available. The average particle momentum even at CEA energies is of the order of 1 GeV; transverse momenta of several hundred MeV characteristic of hadronic interactions would make any such jets rather diffuse in nature. It was suggested some time ago by Bjorken and Brodsky[19] that a statistical test for jets might be useful even though the visual impression may not be clear. The technique is to look for nondegenerate eigenvalues of the tensor

$$T_{\alpha\beta} = \sum_{\text{particle-i}} \left(\frac{3}{2} p^i_\alpha p^i_\beta - \frac{1}{2} \delta_{\alpha\beta} \vec{p}^{\,i2}\right) \Big/ \sum_i \vec{p}^{\,i2} .$$

Such a test seeks a nonvanishing quadrupole moment in the angular distribution of the hadrons of a single event. To my knowledge this test has not been attempted nor do I have a qualitative feeling for the sensitivity of such a test. Only experimenters having raw data can perform this test on the model, and one would hope that results could be forthcoming in the near future. In the mean time the observed multiplicity distribution speaks in favor of this model.

Another topic which has received much attention recently is the existence of a new vector meson, the ρ'. To storage ring people such an object manifests itself as a broad enhancement in the yield of four charged pions as shown in Fig. 7. The relative merits of the photoproduction data and the storage ring data indicating the existence of the ρ' have been debated elsewhere by people more closely related to the subject than myself, so I shall not enter into this discussion. Suffice it to say that in principle a colliding beam experiment could be a valuable tool for such an investigation, but considerably higher statistics are required to put the ρ' on any kind of footing like the ρ. One could also study the channel $\rho' \to \pi^+\pi^-\pi^0\pi^0$, and use this information for isotopic spin assignment. Figure 8 shows data[12,13,16] on this reaction; it is clear that the rate to $\pi^+\pi^-\pi^+\pi^-$ is about the same as the rate to $\pi^+\pi^-\pi^0\pi^0$. Under certain simplifying assumptions[20] this result favors I = 1 for the ρ'. One very clear advantage of a positive storage ring experiment is the assignment $J^{pc} = 1^{--}$.

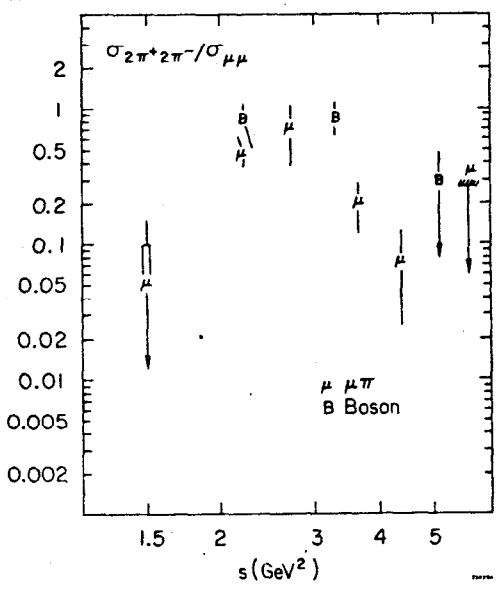

FIG. 7--Annihilation cross section for $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$. Data from Refs. 15, 16.

There is a very pretty piece of physics lurking on the left edge of Fig. 8. The three Orsay points[12] are new and are nicely described by a quasi two body process $e^+e^- \to (\pi^+\pi^-\pi^0)\pi^0$, where the three pion state may be identified

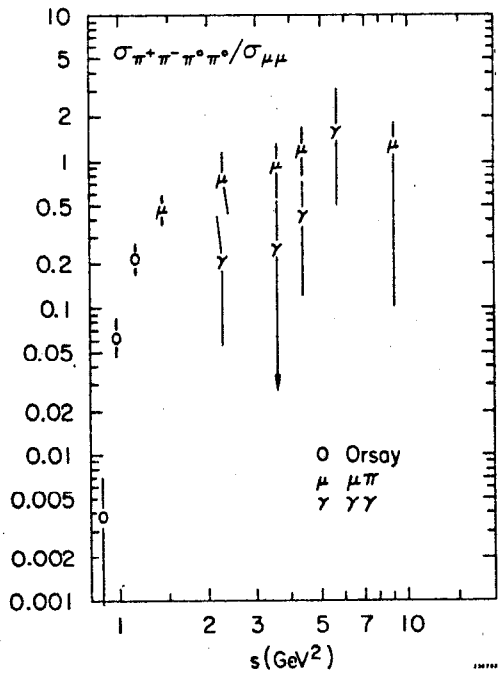

FIG. 8--Annihilation cross section for $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$. Data from Refs. 12, 13 and 16.

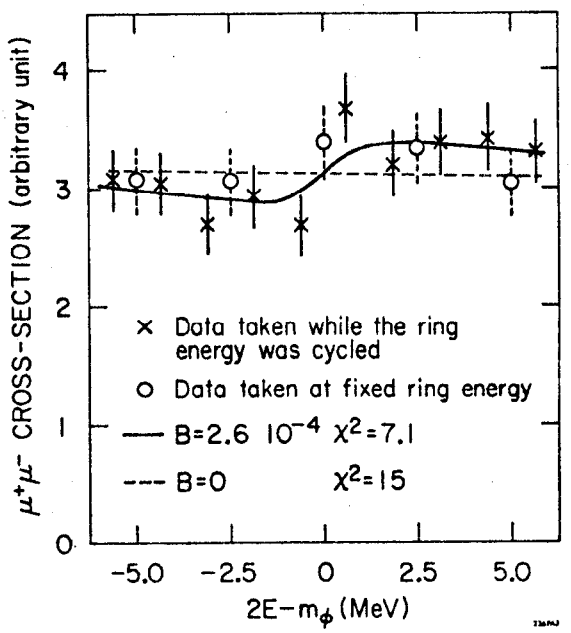

FIG. 9--s dependence of cross section for $e^+e^- \to \mu^+\mu^-$ showing contribution of ω to vacuum polarization (Ref. 23).

with an ω meson. These data are quantitatively fit by a model of Renard.[21] One should note that this model only accounts for the threshold behavior of the reaction and accounts for only about 20% of the yield seen at higher energies. Perhaps it is worth noting that the data presented span about two decades. For experiments which are generally severly limited by data rate this is a remarkable achievement.

The very first results from SPEAR were presented at this conference by a group from UCLA,[22] whose results were obtained by parasitic running during a feasibility test. They wish to study an antinucleon spectrum. During their running on a piece of test apparatus they found one clear $\bar{p}$ event and essentially no background and two $\bar{n}$ candidates, but with substantial background. They thus place 90% confidence upper limits on the total cross sections leading to $\bar{p}$ or $\bar{n}$ final states: $\sigma_{\bar{p}} < 5 \times 10^{-34}\text{cm}^2$ and $\sigma_{\bar{n}} < 2 \times 10^{-33}$.

Generally speaking storage ring experiments to date have been rather straight forward in concept and if difficult or even heroic, not terribly imaginative. In closing, here is a plum recently offered by ORSAY[23] which is all of the above <u>except</u> unimaginative. By making very accurate measurements of the s dependence of $e^+e^- \to \mu^+\mu^-$ near the ϕ mass they observed the contribution to vacuum polarization due to the ϕ intermediate state. Their results are shown in Fig. 9.

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