THE TIME-LIKE FORM FACTOR OF THE NUCLEON AND ITS CONSEQUENCES ON THE EXPERIMENTS WITH COLLIDING ELECTRON- POSITRON BEAMS

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(Presented by A. Zichichi)

Colliding electron-positron beams provide a powerful tool for the investigation of the electromagnetic structure of elementary particles. A typical diagram which illustrates the colliding beam processes is the following (see Fig. 1) in which an electron-positron pair annihilates into a virtual photon, a vector particle V is created and decays into two other particles m_1 and m_2.

One could ask why it is so important to study electromagnetic structures. Nobody knows how to predict the structure of an elementary particle. In fact this structure is expected to be very complicated. The electromagnetic field selects only the vector structure of a particle because the photon has $J^P = 1^-$. Moreover the interaction of the electromagnetic field consists of an isoscalar and an isovector part and therefore, from the isotopic point of view, only isovector and isoscalar structures can be investigated. The ability of the e.m. field to select a sample of states with quantum numbers

$$J^P = 1^-; \quad C = -1; \quad I = 0,1; \quad B = S = 0$$

out of the many other possible ones, is at the origin of the interest in the electromagnetic structures.

There are four classes of phenomena which are relevant in connection with electromagnetic structures, namely:

— the production of particles in electron-positron colliding beam experiments;

— the leptonic decays of vector resonances;

— proton-antiproton annihilation into lepton pairs;

— elastic electron-nucleon scattering.

To establish a correlation between these four classes of experiments is one of the most outstanding problems in the physics of elementary particles.

From the theoretical point of view this correlation exists if we believe in:

1) gauge invariance;
2) Lorentz invariance and
3) crossing symmetry.

The correlation assumes a very simple form if we believe in:

4) pole dominance in the dispersion integral of the nucleon form factors.

Experimentally, our knowledge comes from:

1) electron nucleon elastic scattering;
2) proton-antiproton annihilation into ($\bar{e}$, e) and ($\bar{\mu}$, μ) pairs;
3) the existence of vector mesons with quantum numbers: $J^P = 1^-$, $C = -1$, $I = 1,0$. (i. e. the well known ρ, ω and Φ).

I will briefly report on an experiment of the second class and then discuss its consequences with respect to colliding beam experiments.

This experiment has been carried out at CERN by M. Conversi, T. Massam, Th. Muller and myself and consisted in the study of the annihilation processes

$$\bar{p} + p \rightarrow \bar{\mu} + \mu \qquad [1]$$

$$\bar{p} + p \rightarrow \bar{e} + e. \qquad [2]$$

The invariant time-like four momentum transfer in this experiment was $q^2 = 6.8$ $(\mathrm{GeV}/c)^2$. The choice of this q^2-value was dictated by the requirement of the maximum number of observable events predicted using the knowledge of $\bar{p}$-fluxes as function of momentum at the CERN PS together with the behaviour of the cross-section as function of $\bar{p}$-momentum for processes

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[1] and [2]. This dependance can be predicted if we assume that the proton has a point-like interaction with the electromagnetic field. For the above value of q^2 the expected point-like cross-section for processes [1] and [2] is (1)

$$\sigma_{\bar{p}p \to \bar{\mu}\mu} = \sigma_{\bar{p}p \to \bar{e}e} = 242 \text{ nbarns} \qquad (\text{nbarn} = 10^{-33}\ \text{cm}^2).$$

This value of the cross-section should be compared with the total annihilation cross-section, which is

$$\sigma_{\bar{p}p - \text{total annihilation}} \simeq 5 \times 10^7 \text{ nbarns},$$

in order to realize the rejection needed to discriminate muons and electrons from pions. In fact the aim of the experiments was to reach a level of about two orders of magnitude lower than the point-like cross-section, i.e., $\simeq 1$ nbarn. This aim imposed the choice of a special high intensity antiproton beam, whose general layout is shown in Fig. 2. The detailed design and performances of this beam-project have already been published (2). The typical figures of the beam were:

1) $\sim 80.000\ \bar{p}$ per 10^{12} circulating protons;
2) production angle $= 111$ milliradians;
3) beam size = 2.5 cm diameter;
4) momentum spread $= \pm 2\%$;
5) burst-length = 200 to 300 milliseconds;
6) repetition rate $= (2.3 \text{ to } 3.0 \text{ sec.})^{-1}$;
7) machine momentum = 19.2 GeV/c;
8) π-contamination $= \pi/\bar{p} = 3.6$.

Fig. 3 shows a typical beam-separator curve, where the $\bar{p}$-peak and the corresponding π-contamination are visible.

A general view and a detailed drawing of the experimental set-up for the detection of the leptonic annihilation processes are shown in Figs. 4 and 5* respectively. The set-up consisted essentially of two electron detectors and two muon detectors, placed symmetrically at 53°, in

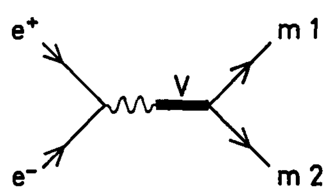

Fig. 1 - A typical diagram illustrating the colliding beam processes.

the laboratory system, with respect to the incident $\bar{p}$-beam direction. This angle corresponded to symmetry about 90° in the c.m. system. The detailed design and performance of these detectors are described in (3) and (4). The electron detector (see Fig. 6) was a system of five elements each containing a lead-layer, a two-gap spark chamber and a plastic scintillation counter. The electromagnetic shower had to originate in the first lead plate, the counters were used to follow the shower development in the successive layers, and the spark-chambers to follow the spatial distribution of the cascade electrons of the shower. With this detector it was possible to identify much of the charge-exchange pion-scattering, thus reducing the most serious source of background which occurs in all non visual detectors; moreover it provided a fast signal proportional to the shower energy. In Fig. 7 the rejection power of this detector against pions is shown as a function of the pion energy. It is about 5×10^{-4} over the energy range defined by the geometry of the apparatus, namely from 1.1 to 2.5 GeV/c.

The combined rejection power of the two « electron » telescopes was therefore $(5 \times 10^{-4})^2 = 2.5 \times 10^{-7}$. This rejection power had to be multiplied by the probability that an antiproton produced in the kinematic chambers two tracks which simulated two-body kinematics. This probability was measured to be 0.7×10^{-4}. The rejection power of the set-up for « electron » detection against total annihilation was therefore:

$$1.75 \times 10^{-11}/\bar{p}.$$

As the total number of incident $\bar{p}$ for the (ee) channel was 4×10^9, the expected number of background events was:

$$1.75 \times 10^{-11} \times 4 \times 10^9 = 7 \times 10^{-2}$$

The above background estimation does not take into account the simulation of electrons by charged-neutral pion pairs, in which the neutral pion converted in the first lead plate and the charged pion track and the shower were so close together that they could not be resolved in the chambers. This background was estimated by scanning the whole film for events in which at least one charged and one neutral pion were observed in each telescope, by selecting those of the events which fitted the two body annihilation angular correlation within the resolution of the experiment and finally by extrapolating the distribution in special separation of the charged and neutral pions in order to estimate how many were not resolved. The cross-section for

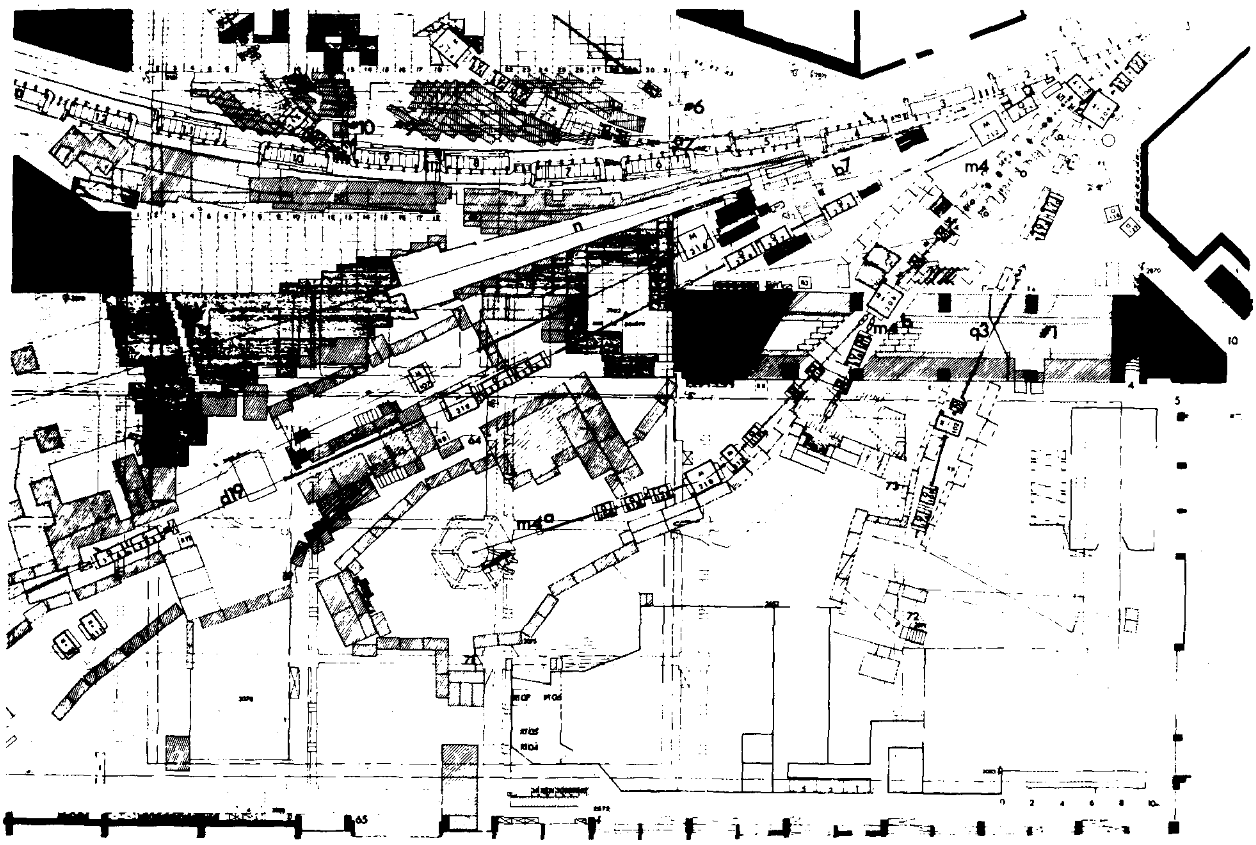

Fig. 2 - Showing the layout of the partially separated antiproton beam, m4$'_a$, used for the experiment.

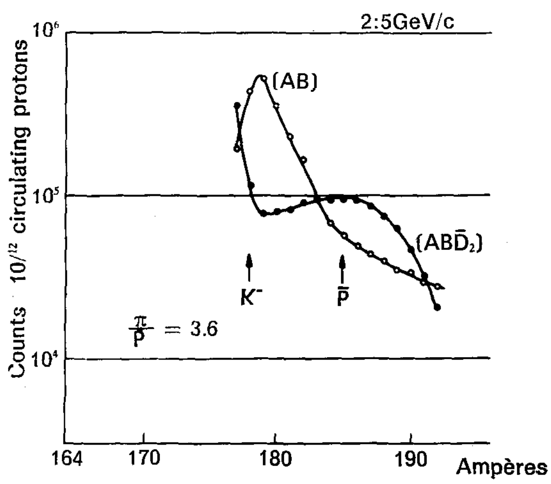

Fig. 3 - Showing the beam intensity as a function of the current in the compensating magnets of the electrostatic separator. (AB) is the total beam intensity ÷ 8, and (AB$\bar{D}_2$) is the intensity after electronic rejection of pions and lighter particles.

this process to simulate the two electron annihilation mode was found to be

$$(0.15 \pm 0.03) \text{ nbarns,}$$

which would have produced (0.6 ± 0.1) event in the whole run.

The electron detectors were also the first part of the muon telescope (see Fig. 5) and were used for kinematic reconstruction in both experiments. Behind them were lead absorbers, shaped according the kinematics of the two body annihilation process (1). Finally there were sets of heavy-plate spark chambers in wich the muon range was measured. The discrimination power of the muon telescopes was studied at various energies and angles. The results are summarized in Table I.

The rejection power against pions of the electron detectors was so good that even with the very pessimistic assumption that all the events in which two particles simulated the two-body angular correlation in the telescopes were due to the two pion annihilation mode, the estimated background was less than 0.1 n barn. In the case of the muon detectors, the rejection power was not as good. Consequently, it was not possible to obtain a meaningful estimate of the up-

TABLE I

Momentum (GeV/c)	Pion penetration
	$\times 10^{-3}$
2.5	1.5
2.5-0.15	1.3
2.5-0.30	1.0
2.1	1.0
2.1-0.15	0.6
2.1-0.30	0.1

Momentum (GeV/c)	Pion penetration
	$\times 10^{-3}$
1.8	6.0
1.8 -0.15	3.7
1.8 -0.30	2.8
1.53	15.0
1.53-0.15	9.4
1.53-0.30	5.5
1.25	17.6
1.25-0.15	10.7

Notation 2.5-0.15 GeV/c, for example, means an incident momentum of 2.35 GeV/c but with the beam incident on the part of the telescope corresponding to 2.5 GeV/c in the two-body annihilation process.

per limit of the background from pion penetration without a detailed knowledge of the spectrum of pions, which were within the angular acceptance chosen for the experiment, but were not associated with other pions which entered either the telescopes or a veto counter which was placed after the target. However, the range of muon energies accepted by the telescopes was sufficiently large that events with lower total energy than that expected for muon events could be observed in order to allow an extrapolation of the background into the good energy region.

One muon-like event was observed, but this was compatible with being par of the background tail and so no two-muon events have been definitely seen. In the electron experiment also, no events were found which could be identified with the two electron annihilation mode.

From now on, we will combine the muon and electron channels into a unique « lepton » channel in order to derive the best limit on the proton time-like form factor for $q^2 = 6.8\ (\text{GeV/c})^2$, and all quantities quoted will be the 90% confidence upper limits. The results are shown in Table II for three different assumptions on the relative magnitudes of the form factors, namely

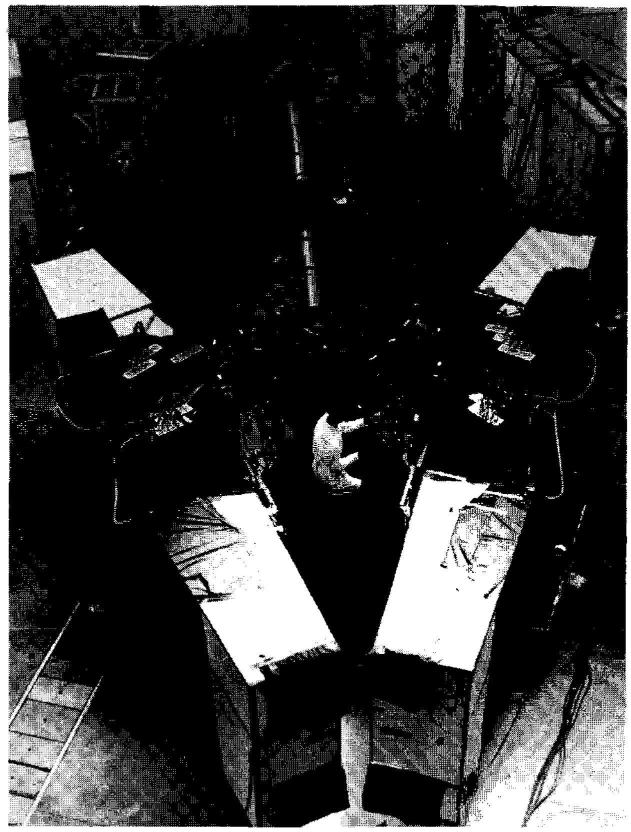

Fig. 4 - Showing a general view of the experiment.

TABLE II

Assumption	$G_{EP} = 0$	$G_{MP} = 0$	$\|G_{EP}\| = \|G_{MP}\|$
Angular distribution	$1 + \cos^2\Theta$	$1 - \cos^2\Theta$	$1 + 0.32\cos^2\Theta$
$\left(\frac{d\sigma}{d\Omega}\right)$ 90° centre of mass	0.032 nbarn/ster.	0.039	0.035
σ Total	0.54 nbarn	0.33	0.48
Value of $\|G\|$	$\|G_{MP}\| = 0.17$	$\|G_{EP}\| = 0.25$	$\|G\| = 0.15$

$|G_{EP}| = 0$, $|G_{MP}| = 0$ and $|G_{EP}| = G_{MP}|$. This last choice gives

$$|G_{EP}| = |G_{MP}| = 0.15$$

The small dependence of the differential cross-section on the assumption used for the form factors is a consequence of the finite angular acceptances of the telescopes.

To summarize, for any relative magnitudes of the form factors, the differential cross-section at 90° in the centre-of-mass system is

$$\left(\frac{d\sigma}{d\Omega}\right)^{\bar{p}p \to \bar{e}e}_{90^\circ \text{ C.M.}} \leqslant 3.9 \times 10^{-35} \text{ cm}^2/\text{steradian},$$

and the total cross-section relative to that for a point-like proton is

$$\frac{\sigma^{\text{experimental}}_{\bar{p}p \to \bar{e}e}}{\sigma^{\text{point like}}_{\bar{p}p \to \bar{e}e}} \leqslant 2.2 \times 10^{-3}$$

The implication of this result for the electron positron colliding beam experiment is immediately obtained by detailed balance which gives a cross-section for the process $e^+e^- \to pp$ of

$$\left(\frac{d\sigma}{d\Omega}\right)^{\bar{e}e \to \bar{p}p}_{90^\circ \text{ C.M.}} \leqslant 3.4 \times 10^{-35} \text{ cm}^2/\text{steradian}$$

at $q^2 = 6.8$ $(\text{GeV})/c)^2$ time-like, which corresponds to 1.3 GeV/c colliding $(e^+ e^-)$ beams, which will be available at the ADONE-machine.

Concerning the comparison of the above results with the Wu and Yang (5) hypothesis of exponential behaviour of form factors, which can be fitted to the space-like data for high values of q^2, and which predicts a value of $|G| \sim 1$ in the time-like region, it is immediately seen that this prediction is in contradiction with our experimental results.

On the other hand, the 4-pole fit obtained by Dunning et al. (6) gives the following predictions for the G's at $q^2 = -6.8$ (GeV c)^2:

$$G_{EP} = 0.06 \qquad G_{MP} = 0.04$$

This prediction is compatible with our result, but the fit may be subjected to the criticism that it is a three-parameter fit, has an unknown vector meson resonance ρ', and does not agree with the known Φ - ω mixing.

We have obtained a fit to all space-like and

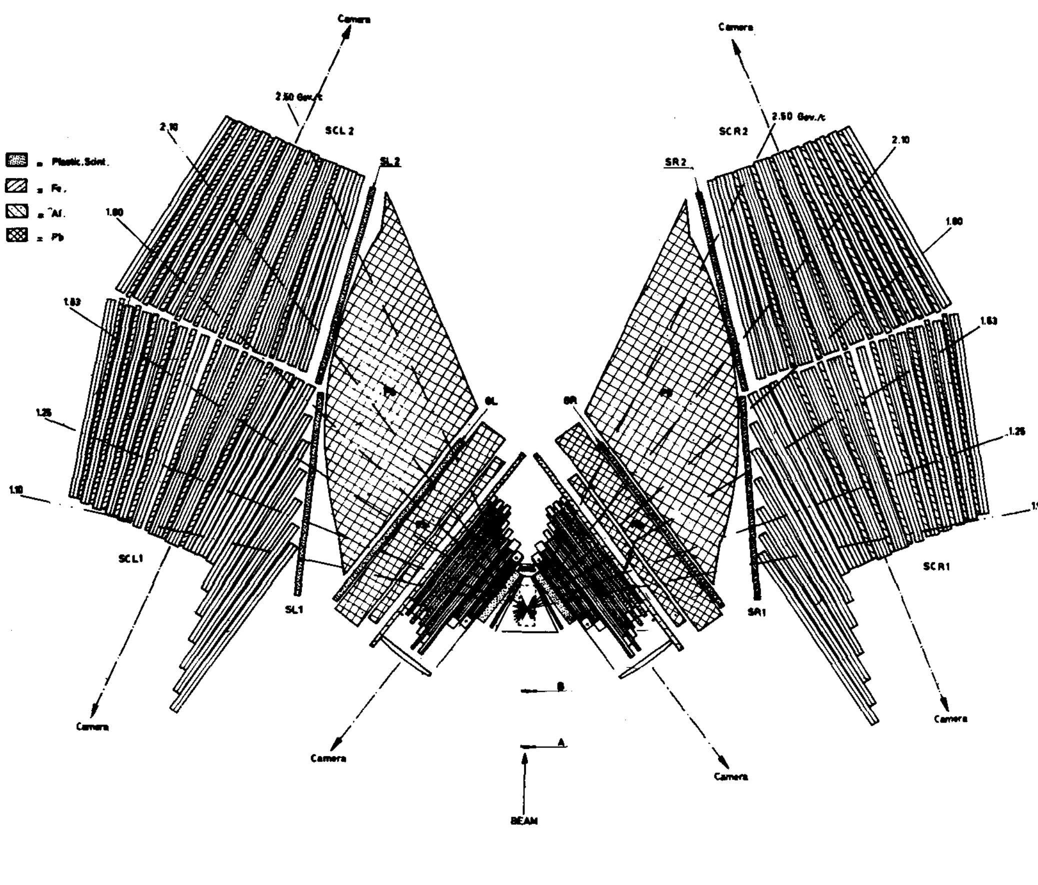

Fig. 5 - Showing a detailed drawing of the experimental set-up.

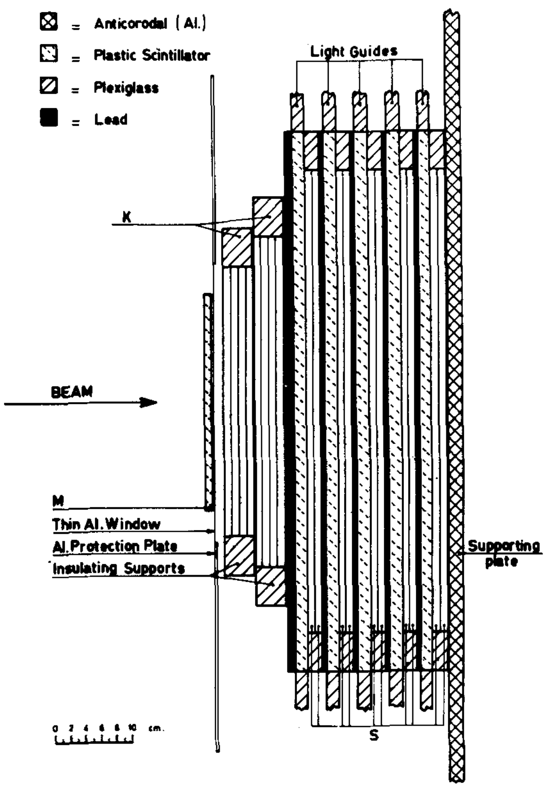

Fig. 6 - Showing a detailed side view of the electron detector.

time-like data by using only the three known vector mesons, ρ, ω, Φ, by using the correct Φ - ω mixing, and by taking into account that the two vertices « vector-meson-photon » and « vector-meson-nucleon » of Fig. 1 cannot be point-like vertices. It turns out that the deviation from point-like coupling has to be different for the « vector-meson-nucleon » interaction depending upon the helicity-flip or non-flip coupling. The deviation from point-like coupling for the electromagnetic vertex of the vector mesons is consistent with being the same for all mesons ρ, ω and Φ. Our fit is a one parameter fit to the experimental data, while all other fits attempted so far are at last 3 parameter fits. The values of the form factors calculated from our fit are even less than the values obtained from Dunning et al., namely:

$$G_{EP} = 0.009, \quad G_{MP} = 0.03 \quad \text{at} \quad q^2 = 6.8\ (\text{GeV/c})^2 \ \text{time-like.}$$

The details of this work will be published elsewhere (7).

Concerning predictions for e^+e^- storage ring experiments, it is obvious that in order to calculate expected rates rather than upper limits as done above, the fit to the form factors must be used. As an example, we will estimate cross-sections for a 1.5 GeV/c storage ring as planned at Frascati, and compare this estimate with the results of the theory of Wu and Yang which previously could not be excluded on experimental grounds. The result is:

$$\frac{\sigma^{\text{This fit}}_{e\bar{e} \to p\bar{p}}}{\sigma^{\text{Wu and Yang}}_{e\bar{e} \to p\bar{p}}} = 2.3 \times 10^{-4}$$

which in terms of absolute cross-section gives:

$$\sigma^{\text{This fit}}_{e\bar{e} \to p\bar{p}} = 3.4 \times 10^{-36}\ \text{cm}^2$$

For 3 GeV/c storage rings, as planned at Stanford, the result is:

$$\frac{\sigma^{\text{This fit}}_{ee \to pp}}{\sigma^{\text{Wu and Yang}}_{ee \to pp}} = 1.5 \times 10^{-6}$$

and in terms of absolute total cross-section:

$$\sigma^{\text{This fit}}_{e\bar{e} \to p\bar{p}} = 4.0 \times 10^{-39}\ \text{cm}^2$$

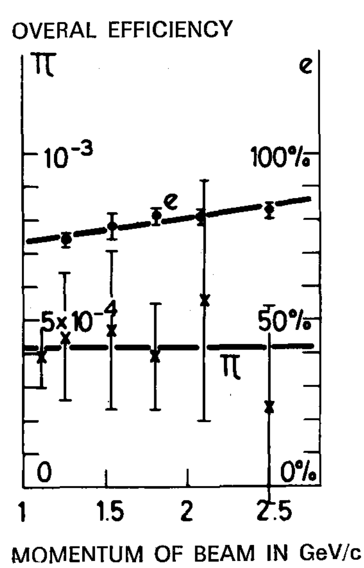

Fig. 7 - Showing the energy dependence of the over-all efficiency of the electron detector, and its rejection power against pions.

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DISCUSSION

O'NEILL: Your final numbers appear to be limits. Does this mean that your answer is not statistically different from no events?

ZICHICHI: Yes.

HUGHES: How many events of annihilation into electrons and muons have you seen?

ZICHICHI: We remain with one event per channel. Our states limits take into account this observation.

JENTSCHKE: How large is the correction for measured μ-mesons which are due to decay of π-mesons?

ZICHICHI: The correction for the two-pions annihilation is very small because this channel is already depressed in the annihilation process. We estimate that the correction for many-pions annihilation is also small. This estimate is based on our calibrations, where, by varying the energy and the decaylength of the π-beam, we check to within 10% experimental observations and calculations.

BERNARDINI C.: It is well known that there are many equivalent good fits in the space-like region giving a completely different behaviour among themselves for the form factors in the time-like part. It could easily be that you looked at a special point where the cross section is deeply depressed.

ZICHICHI: This is not correct. The most recent fits to the space-like data, based on the assumption of pole-dominance, predicts in the time-like region a cross-section about an order of magnitude lower than our upper limit. Previous space-like fits which gave higher cross-sections in the time-like region contained « hard-core » terms, which must now be excluded on the basis of the data obtained at high space-like q^2 by Ramsey, Wilson et al. The only theoretical model which would predict a high cross-section in the time-like region is the one I have already mentioned due to Wu and Yang. This model excludes the possibility of special depression points and is in contradiction with our experimental results.

TOUSCHEK: The 4 points which make up the theory are very heterogeneous. I am reasonable prepared to believe in 1, 2, 3 but I would have no qualms in rejecting 4.

ZICHICHI: I agree on the difference between the last and the first 3 points. But if we reject point 4, we loose the possibility of connecting all 4 classes of experiments. The relevance of point 4 is due to the fact that if the background in the dispersion integral of the nucleon form-factors is big, then a great trend in our present line of thought looses any possibility of experimental verification. This main trend is in fact the validity of our first three points. Notice how beautiful would be to have a check of all these three fundamental invariance principles for a large range of q^2 values.