EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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ABSTRACT

Analysing a sample of 220,000 events from an experiment still in progress at the CERN Proton Synchrotron (PS), 60 pairs of electrons with an energy above 700 MeV have been observed. The electrons, produced by annihilation of antiprotons stopped in a liquid-hydrogen target, are detected with optical spark chambers and scintillation counters. Twenty-nine of these 60 pairs have been found to be collinear; normalizing with respect to the hadronic two-body channels $\pi^+\pi^-$ and K^+K^-, a branching ratio

$$B_{ee} = \frac{\Gamma(\bar{p}p \to e^+e^-)}{\Gamma(\bar{p}p \to \text{total})} = (3.2 \pm 0.9) \times 10^{-7}$$

has been obtained.

Twenty-six of the remaining electron pairs can be attributed to the reaction $\bar{p}p \to V^0(e^+e^-) + \pi^0$. The analysis of the data supports the existence of the $\rho''(1600)$ and $\rho'(1250)$ mesons.

The proton electromagnetic form factor G at q^2 between -3.75 and -3.6 has been evaluated on the hypothesis of $G_E = G_M = G$. The value $G = 0.45 {}^{+0.20}_{-0.13}$ has been found.

INTRODUCTION

We present here some results from a systematic study of antiproton-proton annihilation in electron pairs and gamma-rays at rest.

Our main goal is the determination of the proton electromagnetic form factors at the threshold of the time-like region $[q^2 = -3.5\ (\text{GeV/c})^2]$, using the reaction

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

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Why at threshold? The reasons are twofold:

i) At $q^2 = -4M^2$, the charge G_E and the magnetic G_M form factors are equal*): $G_E = G_M = G$ and real. G can be extracted directly from the annihilation rate $\Gamma_{ee} = \Gamma(\bar{p}p \to e^+e^-)$, to which it is related by

$$G = \frac{1}{\alpha}\sqrt{\frac{Mp}{\pi}\frac{\Gamma_{ee}}{\beta}} ,$$

where α is the fine structure constant, M is the proton mass, and p the momentum.

ii) The inverse reaction: $e^+e^- \to \bar{p}p$ cannot be studied at such a low q^2 value, since the final-state protons need a minimum energy in order to be revealed. Our experiment is therefore complementary to any e^+e^- colliding beam research in this field.

How can we obtain Γ_{ee} at rest? At zero incident momentum, detecting collinear electron pairs we measure the branching ratio $B_{ee} = \Gamma_{ee}/\Gamma_{tot}$. But Γ_{ee} can be written as

$$\Gamma_{ee} = \frac{B_{ee}}{B_{hh}} \Gamma_{hh} ,$$

where $B_{hh} = \Gamma_{hh}/\Gamma_{tot}$ is the known (Ref. 1) branching ratio into hadron pairs $(\pi^+\pi^- + K^+K^-)$, and Γ_{hh} is the $\bar{p}p$ annihilation rate into two hadrons at rest $(q^2 = -4M^2)$. This quantity is not yet known. Since

$$\Gamma_{hh}(-4M^2) = \lim \beta\, \sigma_{hh},\ \beta \to 0 ,$$

we intend to obtain Γ_{hh} at rest by extrapolation of Γ_{hh} measurements in several momentum intervals approaching zero.

Finally, we wish to give an experimental answer to the question of the relative contribution of s- and p-states to $\bar{p}p$ annihilation at threshold. Therefore we study the process $\bar{p}p \to \pi^0\pi^0$ at rest, since this mode should be forbidden for annihilations starting from an s-state.

DATA TAKING

Data have been collected in an experiment still in progress at the CERN PS on the following processes:

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

$$\bar{p}p \to h^+h^- \ (h^+h^- = \pi^+\pi^- + K^+K^-) \qquad (2)$$

$$\bar{p}p \to \pi^0\pi^0 . \qquad (3)$$

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*) $G_E = F_1 - (q^2/4M^2)F_2$
$G_M = F_1 + F_2$.

Data on the reaction

$$\bar{p}p \to V^0 + \pi^0 \quad (4)$$
$$\hookrightarrow e^+e^-$$

were obtained with the same electronic trigger as for reaction (1). Events of the type

$$\bar{p}p \to n\gamma \quad (5)$$

have been recorded at the same time as those of type (3).

The experimental apparatus used is essentially the same for all the experiments. It consists of four equal electromagnetic detectors, composed of optical spark chambers, absorbers, and scintillators surrounding a 50 cm liquid hydrogen target, in which a $\bar{p}$ beam is brought to rest. A more detailed description of our set-up has already been published (see Refs. 1 and 2).

To detect reactions (3) and (5), we add to the set-up a veto counter around the target and a one-radiation length converter. To study $\bar{p}p$ annihilation in hadrons, a 2 cm target replaces the standard one.

We have collected ∿ 30,000 pictures for reaction (2) and about 40,000 pictures for processes (3) and (5). Analysis is in progress for both cases. To study reactions (1) and (4) we have collected 220,000 photographs; scanning this sample, we have selected the pictures showing two electrons in opposite blocks. Note that the rejection of the apparatus against hadrons is 2.5×10^{-7}, as extensively explained elsewhere (Refs. 2 and 3).

Preliminary results have already been published.

RESULTS

Sixty electron pairs with energy above 700 MeV have been reconstructed in space. Figure 1 shows the opening angle distribution of the whole sample.

Three types of background could contribute to this spectrum:

i) Electron simulation. One electron can be simulated by several processes:

- a charged pion giving an interaction or a charge exchange;
- a superposition of a pion and a γ-ray from the same annihilation;
- a converted γ-ray;

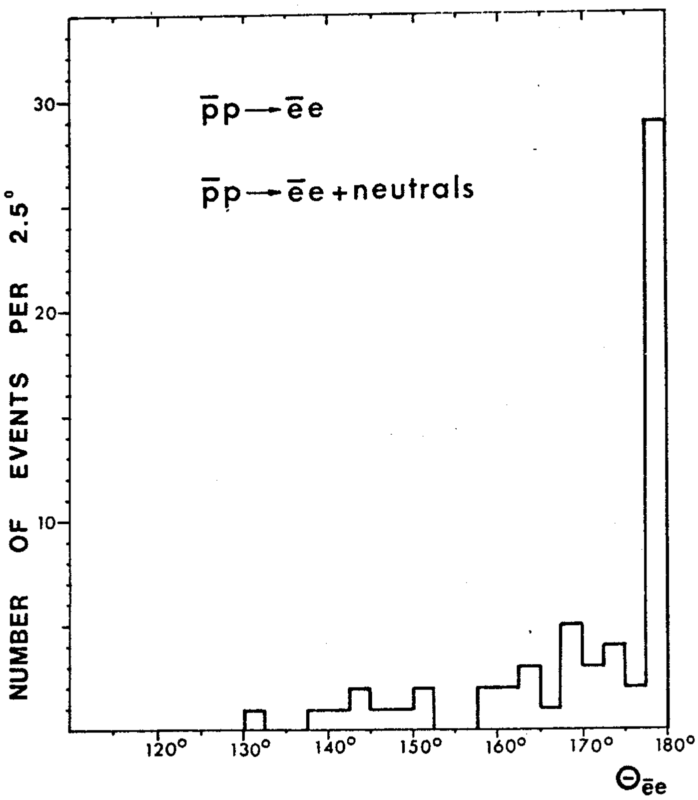

Fig. 1. Opening angle distribution of the 60 electron pairs.

ii) One electron of a Dalitz pair;

iii) Two correlated electrons. The only processes to take into consideration are K^+K^- pair production where both kaons decay via $K^{\pm}_{e3}$, or a large-angle Dalitz pair produced by one π^0.

Each of the sources of uncorrelated background was studied separately by Monte Carlo calculations and by measurements on our data or on our calibrations. None of them contributes to the whole sample by more than one event. Moreover, we have a very reliable over-all estimate of these types of background by counting the number of single "electrons" in our photographs. By single "electron" we mean an event where the particle in one detector has all the characteristics of an electron and the particle in the opposite detector is clearly a pion or a converted γ-ray. In 1000 photographs, we find an average of 3.0 single "electrons", corresponding to a simulation of approximately two electron pairs in our sample of 2.2×10^5 pictures. Since the opening angles between single "electrons" and corresponding pions or gamma-rays show a flat distribution between 130° and 180°, two events mean 0.4% contamination of the collinear sample and less than 7% for the remaining 31 pairs.

The sources of background of the type (iii), where the two electrons have some correlation, were estimated by Monte Carlo calculation and found to contribute by less than 1‰ to the whole sample of events for electrons of energy above 400 MeV with opening angle larger than 120°.

Figure 2 shows the $\theta_{\bar{e}e}$ distribution for electron pairs coplanar with the beam direction within ±6.5° and with no visible gamma-ray in the picture. The 29 collinear electrons coming from $\bar{p}p$ annihilation at rest are accumulated at 180°.

The other five events, distributed between 155° and 180°, are likely to be produced in $\bar{p}p$ annihilation in flight. The continuous line shows in fact the expected opening angle distribution for pairs produced in flight, following the calculation of Bogdanova et al. (Ref. 4), and using the measured momentum spectrum of $\bar{p}$ entering the target.

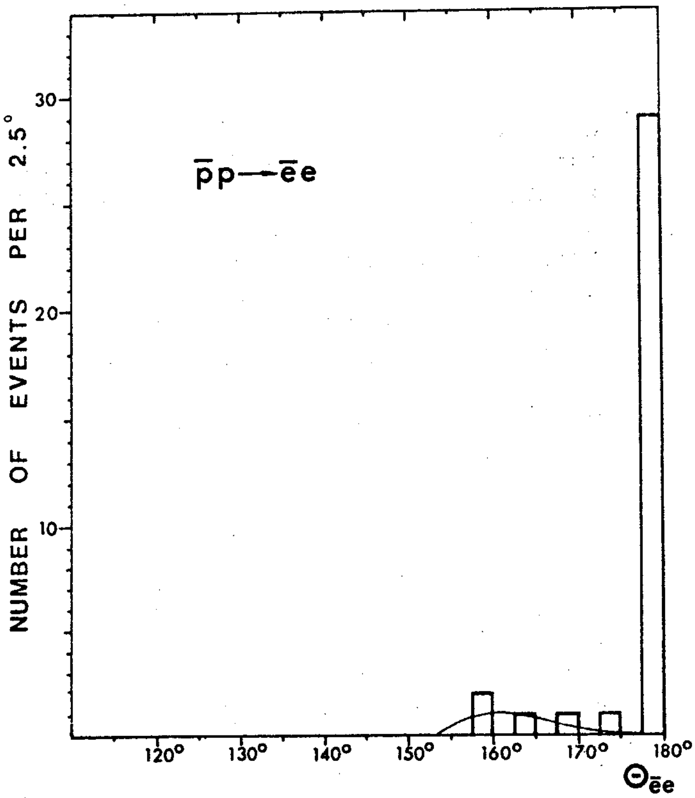

Fig. 2. Opening angle distribution of the coplanar electron pairs. The curve represents the distribution expected for e^+e^- pairs produced by antiprotons in flight.

This distribution is verified with high statistics in the data taken for the process $\bar{p}p \to h^+h^-$ at rest, detected with our apparatus. The spectrum of the opening angles between the two hadrons is shown in Fig. 3.

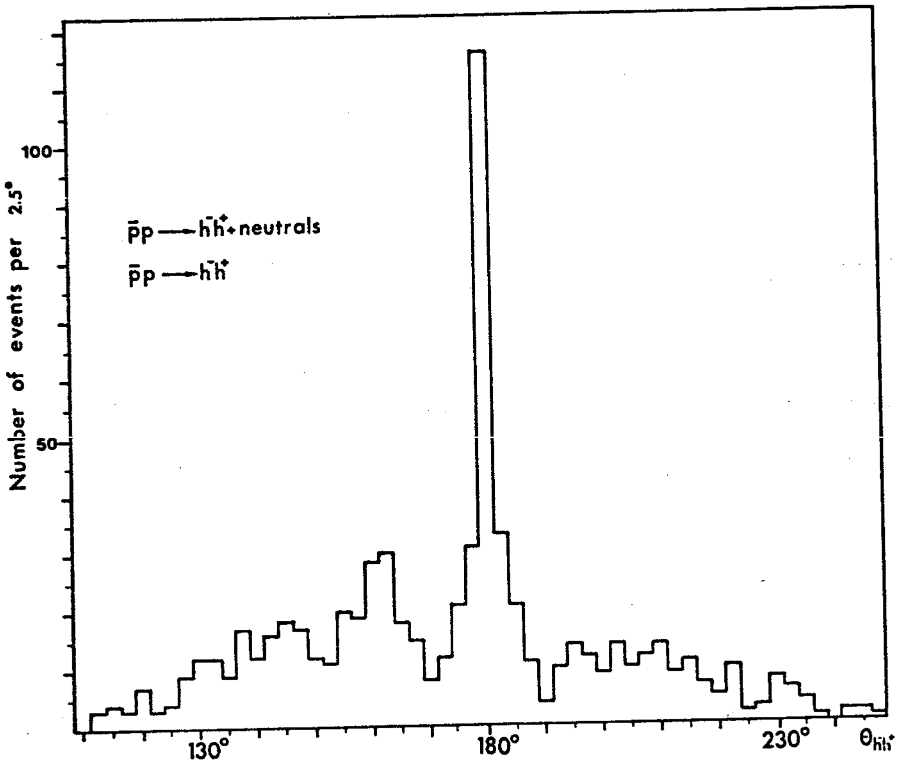

Fig. 3. Opening angle distribution of hadron pairs

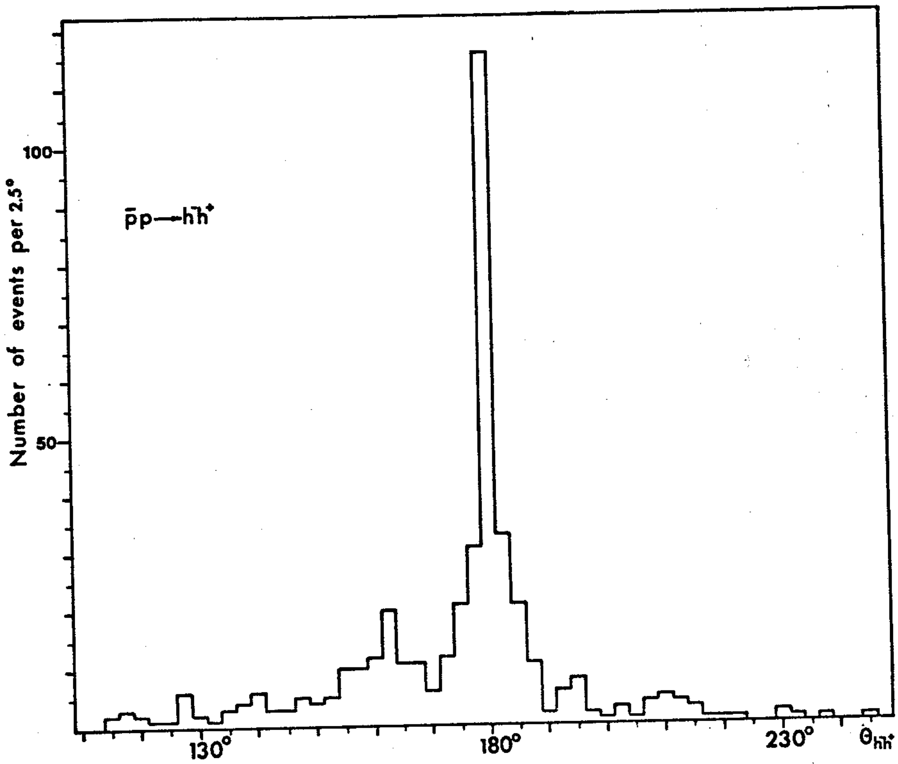

Fig. 4. Opening angle distribution of hadron pairs applying a cut in the coplanarity angle.

A clear peak in the collinear region (around 180°) allows an unambiguous selection of the events corresponding to annihilations at rest into h^+h^-. The excess of events in the forward region (with respect to the incoming beam direction), between 153° and 171°, corresponds to h^+h^- produced by antiprotons annihilating in flight, with momentum between 150 and 450 MeV/c.

In fact, if we decrease the many-body background by requiring a coplanarity angle within ±10° between the plane of the annihilation products and the beam line, we obtain the opening angle spectrum shown in Fig. 4.

We have evaluated the branching ratio B_{ee} on the basis of 29 electron pairs, normalizing to 240 events of the reaction at rest $\bar{p}p \to h^+h^-$. With this method we eliminate important instrumental uncertainties, such as the fraction of stopping $\bar{p}$, solid angle, and M counter efficiency.

We obtain

$$\frac{\Gamma(\bar{p}p \to e^+e^-)}{\Gamma(\bar{p}p \to h^+h^-)} = (0.74 \pm 0.2) \times 10^{-4}$$

and, using the known branching ratio into h^+h^- (see Ref. 1), we derive

$$B_{ee} = \frac{\Gamma(\bar{p}p \to e^+e^-)}{\Gamma(\bar{p}p \to \text{total})} = (3.2 \pm 0.9) \times 10^{-7} .$$

If the contribution to the spectrum of Fig. 1 from reaction (1) produced in flight or at rest is removed, selecting the electron pairs acoplanar with the beam direction, or/and showing a γ-ray in the picture, we are left with 26 events, distributed in $\theta_{\bar{e}e}$, as shown in Fig. 5 (Ref. 5).

Since only two background events can contribute to the whole sample, the spectrum is mainly due to interactions of the type

$$\bar{p}p \to V^0 + \pi^0, \quad V^0 \to e^+e^- .$$

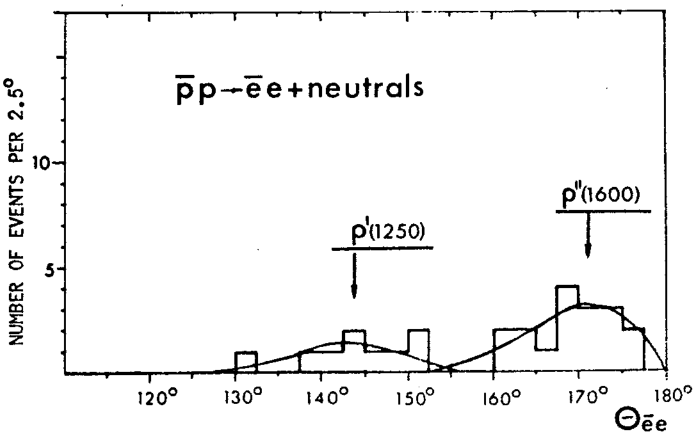

Fig. 5. Opening angle distribution of the acoplanar electron pairs. The solid curves represent fits to the data assuming the production of two vector mesons of mass 1600 MeV (Γ = 300 MeV) and 1250 MeV (Γ = 150 MeV).

Processes involving more than one π^0 or higher mass neutrals are strongly depressed by phase space and by the electron energy cut at 700 MeV. The ρ, ω, and φ vector mesons do not contribute to our sample, since they are practically out of our acceptance.

To determine the mass and the width of the objects produced in reaction (4), we have fitted the $\theta_{\bar{e}e}$ spectrum (Fig. 5) with the opening angle distribution calculated assuming Breit-Wigner mass distributions and isotropic production and decay. Assuming that only one vector meson, with mass $M \sim 1600$ MeV and width $\Gamma \sim 300$ MeV, is produced, the best fit yields a probability of 12%. Introducing a second vector meson with $M \sim 1250$ MeV and $\Gamma \sim 150$ MeV, we obtain a probability of 80%. The best fits, represented by continuous lines in Fig. 5 give the following masses and widths:

$$M_{\rho'(1250)} = (1250 \pm 50)\ \text{MeV}, \quad \Gamma_{\rho'(1250)} \sim 150\ \text{MeV}$$

$$M_{\rho''(1600)} = (1600 \pm 50)\ \text{MeV}, \quad \Gamma_{\rho''(1600)} \sim 300\ \text{MeV}\ .$$

The production of the $\rho''(1600)$ meson seems thus established in $\bar{p}p$ annihilations, and its decay mode into e^+e^- is observed here for the first time. The existence of the $\rho'(1250)$ is supported by our results, but a clear-cut statement requires more statistics.

We have evaluated the branching ratio:

$$B_{\rho''} = \frac{\Gamma(\bar{p}p \to \rho'' + \pi^0)}{\Gamma(\bar{p}p \to \text{total})}$$

assuming $\Gamma[\rho''(1600) \to e^+e^-] = \Gamma[\rho(760) \to e^+e^-]$. Comparing this to the branching ratio for $\bar{p}p \to e^+e^-$ at rest, we obtain

$$B_{\rho''} = (0.5\text{-}1)\%\ .$$

CONCLUSIONS

To extract a value of G at $q^2 = -4M^2$, we intend, as explained in the Introduction, to obtain the value of Γ_{hh} at rest by extrapolation of our measurements of Γ_{hh} in flight at several small momenta. For the time being, let us derive a rough value of G at ~ 400 MeV/c from the fact that we observe in Fig. 2 three coplanar electron pairs with opening angles between 155° and 165°, corresponding to antiproton momenta between 500 MeV/c $[q^2 = 3.75\ (\text{GeV/c})^2]$ and 300 MeV/c $[q^2 = 3.6\ (\text{GeV/c})^2]$. In the same opening angle range we observe in our h^+h^- data 50 ± 10 events. Thus we obtain

$$\frac{\Gamma_{ee}}{\Gamma_{hh}} = \left(0.4 \begin{array}{l} +\ 0.32 \\ -\ 0.2 \end{array}\right) \times 10^{-4} \text{ at } 400\ \text{MeV/c}\ .$$

If we take the known (Ref. 6) value of σ_{hh} at 400 MeV/c of ~ 0.9 mb, we derive

$$\sigma_{ee} = \left(36 \begin{array}{l} +\ 30 \\ -\ 20 \end{array}\right) \text{nb at } (400 \pm 100)\ \text{MeV/c}\ ,$$

which corresponds to

$$G = 0.45 \begin{array}{l} +\ 0.20 \\ -\ 0.13 \end{array}\ ,$$

if we assume $G_E = G_M$ at this momentum.

This value of G is compared in Fig. 6 to the ADONE (Ref. 7) value and to the BNL (Ref. 8) and CERN (Ref. 9) upper limits. A G value obtained from the DORIS (Ref. 10) data at $q^2 = -9.6\ (GeV/c)^2$, corresponding to the ψ/J, is also represented. It is derived assuming $G_E = G_M$ and comparing the ratio $\Gamma(e^+e^- \to \bar{p}p)/\Gamma(e^+e^- \to \mu^+\mu^-)$ measured at DORIS to the same ratio measured at ADONE at $q^2 = -4.3\ (GeV/c)^2$.

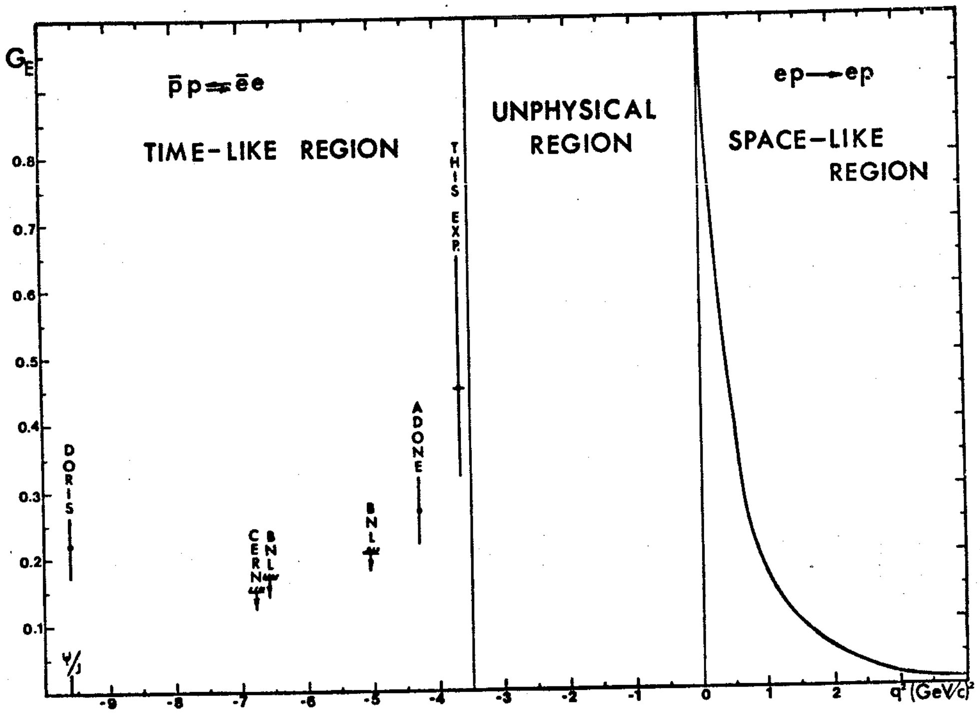

Fig. 6. The proton form factor $G_E(q^2)$. The continuous line represents the numerous experimental points obtained in ep scattering.

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