UPPER LIMITS OF THE PROTON MAGNETIC FORM FACTOR IN THE TIME-LIKE REGION FROM $\bar{p}p \to e^+e^-$ AT THE CERN-ISR

Anncy (LAPP)—CERN—Genoa—Lyon (IPN)—Oslo—Roma—Strasbourg—Torino Collaboration

C BAGLIN a, S BAIRD b, G BASSOMPIERRE a, G BORREANI c, J.C. BRIENT a, C BROLL a,1, J.M. BROM d, L BUGGE e, T. BURAN f, J.P. BURQ f, A. BUSSIÈRE a, A BUZZO g, R. CESTER c, M. CHEMARIN f, M. CHEVALLIER f, B. ESCOUBES d, J. FAY f, S FERRONI g, V. GRACCO g, J.P. GUILLAUD a, E. KHAN-ARONSEN b, K. KIRSEBOM e, B. ILLE f, M. LAMBERT f, L LEISTAM b, A. LUNDBY b, M. MACRI g, F. MARCHETTO c, L. MATTERA g, E. MENICETTI c, B. MOUELLIC b, N. PASTRONE c, L. PETRILLO h, M.G. PIA g, M. POULET a, A. POZZO g, G. RINAUDO c, A. SANTRONI g, M. SEVERI h, G. SKJEVLING e, S. STAPNES e, B. STUGU e, F. TOMASINI g and U. VALBUSA g

" LAPP, F-74019 Annecy-le-Vieux Cedex, France
b CERN, CH-1211 Geneva 23, Switzerland
c University of Turin, 1-10124 Turin, Italy
d CRN, F-67037 Strasbourg Cedex, France
e University of Oslo, N-1000 Oslo 3, Norway
f IPN Lyon, Villeurbanne, France
g University and INFN, I-16126 Genoa, Italy
h University of Rome, I-00100 Rome, Italy

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The study of the proton electromagnetic form factors $F_{1,2}(Q^2)$ is of great importance for the understanding of the structure of this particle. Since the pioneer work of Hofstadter and co-workers in 1955 on the $e^-p$ elastic scattering [1], many experiments have produced data [2] on the electromagnetic form factors in the space-like region. On the other hand, in the time-like region, the existing measurements are relatively poor. Antiproton annihilation experiments performed at CERN [3] and BNL [4] gave only upper limits at $Q^2 = +6.8$, $+6.6$ and $+5.1$ (GeV/c)². The first positive results were obtained in 1972 for an $e^+e^-$ colliding beam experiment at Frascati [5] at $Q^2 = +4.3$ (GeV/c)² and was confirmed later by four points in the same energy region, measured at DCI in 1978 [6]. In the inverse channel $\bar{p}p \to e^+e^-$, the first result was obtained at CERN [7] in 1976. Two points were measured: one at threshold ($Q^2 = 4M_p^2$) and the other at $Q^2 = +3.61$ (GeV/c)². Finally, a recent measurement at CERN using the LEAR facility [8] confirms the previous threshold measurement.

The data in the time-like region are essential for determining the analytic function $F(Q^2)$ in the whole complex $Q^2$-plane. Although the data at and near the threshold are fundamental, the asymptotic behaviour of the form factors is also very important. For this

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reason, we have extracted from $\bar{p}p \rightarrow e^+e^-$ data at the CERN-ISR, upper limits of the magnetic form factor $G_M$ (assuming $G_E = 0$) at $Q^2 \approx 8.86$ (GeV/c$^2$) and $Q^2 \approx 12.48$ (GeV/c$^2$).

The experiment was primarily devoted to charmonium spectroscopy through the formation channel $\bar{p}p \rightarrow e^+e^-$ [9]. Electromagnetic final states ($e^+e^-$, $e^+e^-X$, $\gamma\gamma$) were chosen in order to have the best signal/noise ratio. The $\psi, \chi_1(3P_1), \chi_2(3P_2)$ and $\eta_c$ resonances were studied. An attempt to see the singlet $1P_1$ state was made. For the whole study, an inclusive $e^+e^-$ trigger was set during the energy scans and gave data ON and OFF the resonances.

The experiment was performed at the ISR using the CERN $\bar{p}$ complex. The intense $\bar{p}$ beam (few mA) circulating in the ring 2 of the ISR, permanently cooled and interacting with a hydrogen jet-target, allowed to reach a luminosity of $3 \times 10^{30}$ cm$^{-2}$ s$^{-1}$. With such a luminosity, cross sections of the order of a few pb can be measured, corresponding to form factors in the (0.01-0.10) range. The detector [10] is a two-arm non-magnetic spectrometer complemented by a large-acceptance veto system and a silicon detector telescope to monitor the source luminosity. Each of the two identical arms consists of an upstream section for tracking charged particles followed by an electromagnetic calorimeter. Its $e^+e^-$ geometrical acceptance is of the order of 0.10 (of 4$\pi$).

At the trigger level, events were selected by requiring an ARM1 * ARM2 coincidence, where ARM1 is a coincidence of a four scintillator hodoscopes and an atmospheric pressure FREON 13 Cherenkov counter to tag electrons.

Data at the $J/\psi$ formation energy through the channel $\bar{p}p \rightarrow e^+e^-$ were accumulated in various runs. In principle these data could allow the relative determination of $|G_E|$ and $|G_M|$ by fitting the center-of-mass angular distribution, and therefore to test the magnetic form factor dominance predicted by perturbative QCD [11], and observed at the $J/\psi$ by the MARK II Collaboration [12]. Unfortunately this dominance, which corresponds asymptotically to a $1 + \cos^2 \theta$ distribution, cannot be clearly observed in our data due to the poor angular acceptance $[-0.57 \leq \cos \theta \leq 0.57]$. Nevertheless, we keep this $G_M$ dominance hypothesis and from now on, we assume $G_E = 0$ in the interpretation of the results.

Data near the $\eta_c$ [$Q^2 = 8.81-8.92$ (GeV/c$^2$)] corres-

Table 1

| Sample | $Q^2$ range (GeV/c$^2$) | Integrated luminosity (nb$^{-1}$) | Number of events | $|G_M|$ (pb) |
|--------|-------------------------|-----------------------------------|-----------------|------------|
| I      | 8.81–8.92               | 653                               | 0               | 34.5       | 0.052      |
| II     | 12.32–12.65             | 2276                              | 1 a)            | 15.0       | 0.042      |

a) This could be a $\chi_1$ event (see text).
where $E(\cos \theta)$ is the total efficiency. The angular dependence of this efficiency can be factorized out.

For the estimation of the upper limit of $|G_M|$ we ignore this $f(\cos \theta)$ function and take for $E$ its average value $E = 0.94$.

$$N = L E \int_{\theta_1}^{\theta_2} d\phi \int_{|\cos \theta_1|}^{|\cos \theta_2|} \frac{d\sigma}{d \cos \theta} E(\cos \theta) d \cos \theta,$$

with $E$ and $P$ in GeV or GeV/c, $L$ in nb$^{-1}$, $\Delta \phi = \pi/2$.

For the "sample I".

$$\langle Q^2 \rangle = 8.86 \ (GeV/c)^2, \ \cos \theta_2 = - \cos \theta_1 = 0.54,$$

$$L = 653 \ nb^{-1}.$$

The $\cos \theta$ values are also averaged values corresponding to $\langle Q^2 \rangle$. If we take $N \leq 2.36$ events (90% confidence level)

$$|G_M| \leq 0.052 \ at \ 90\% \ CL,$$

and

$$\sigma_T(\bar{p}p \rightarrow e^+e^-) \leq 34.5 \ pb.$$

For the "sample II"

$$\langle Q^2 \rangle = 12.48 \ (GeV/c)^2, \ \cos \theta_2 = - \cos \theta_1 = 0.58,$$

$$L = 2276 \ nb^{-1}.$$

We observed at best one event i.e. $N \leq 3.89$ at 90% CL, thus

$$|G_M| \leq 0.042 \ at \ 90\% \ CL,$$

and

$$\sigma_T(\bar{p}p \rightarrow e^+e^-) \leq 15.0 \ pb.$$

The results are shown in fig. 1 where the previous results in $|G_M| [3-8]$ in this time-like region are also reported.

It is interesting to compare with the QCD predic-

$$\frac{\phi_2}{\phi_1} \int_{|\cos \theta_1|}^{|\cos \theta_2|} \frac{d\sigma}{d \cos \theta} \ E(\cos \theta) \ d \cos \theta,$$

for which the asymptotic behaviour, derived on the basis of the general arguments of the quark counting rule [15], is of the form $|G_M| \propto 1/Q^4$.

$$\langle Q^2 \rangle \propto 1/Q^4$$

The solid curve on the figure represents this $1/Q^4$ dependence arbitrarily normalized to the experimental value of $|G_M|$ at $Q^2 = 5 \ (GeV/c)^2$.

In conclusion, if we believe in the perturbative QCD and make $1/Q^4$ extrapolations from the actual values of $|G_M|$, we can observe that we are not very far from recording real events corresponding to $\bar{p}p \rightarrow e^+e^-$ and contributing to the proton magnetic form factor in the time-like region. The experimental method we used, seems very promising for this kind of physics.

We would like to mention that we obtained in our experiment, as a by-product of a few weeks of data-taking, lower limits than previous dedicated experiments standing for a long time in classical $\bar{p}$ beams.

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