Measurements of the magnetic form factor of the proton for timelike momentum transfers

M. Andreotti,[b] S. Bagnasco,[c] W. Baldini,[b] D. Bettoni,[b] G. Borreani,[g] A. Buzzo,[c] R. Calabrese,[b] R. Cester,[g] G. Cibinetto,[b] P. Dalpiaz,[b] G. Garzoglio,[a] K. Gollwitzer,[a] M. Graham,[e] M. Hu,[a] D. Joffe,[f] J. Kasper,[f] G. Lasio,[d] M. Lo Vetere,[c] E. Luppi,[b] M. Macrì,[c] M. Mandelkern,[d] F. Marchetto,[g] M. Marinelli,[c] E. Menichetti,[g] Z. Metreveli,[f] R. Mussa,[b,g] M. Negrini,[b] M. Obertino,[g] M. Pallavicini,[c] N. Pastrone,[g] C. Patrignani,[c] S. Pordes,[a] E. Robutti,[c] W. Roethel,[f,d] J. Rosen,[f] P. Rumerio,[f] R. Rusack,[e] A. Santroni,[c] J. Schultz,[d] S. H. Seo,[e] K. K. Seth,[f] G. Stancari,[a,b] M. Stancari,[d,b] A. Tomaradze,[f] T. Vidnovic III,[e] S. Werkema[a] and P. Zweber[f]

[a] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[b] *Istituto Nazionale di Fisica Nucleare and University of Ferrara, 44100 Ferrara, Italy*

[c] *Istituto Nazionale di Fisica Nucleare and University of Genova, 16146 Genova, Italy*

[d] *University of California at Irvine, California, 92697*

[e] *University of Minnesota, Minneapolis, Minnesota 55455*

[f] *Northwestern University, Evanston, Illinois 60208*

[g] *Istituto Nazionale di Fisica Nucleare and University of Torino, 10125 Torino, Italy*

Abstract

Fermilab experiment has measured the cross section for the reaction $\overline{p}p \to e^+e^-$ at $s = 11.4, 11.9$, and $12.4\ \mathrm{GeV}^2$. From the analysis of the 42 observed events, new high-precision measurements of the proton magnetic form factor are obtained.

Key words: nucleon, form factors
PACS: 13.40.Gp, 13.75.Cs, 14.20.Dh

Preprint submitted to Elsevier Science *5 September 2002*

The electromagnetic properties of the proton are studied by measuring the electric and magnetic form factors $G_E(q^2)$ and $G_M(q^2)$ as a function of the four-momentum transfer q^2. In the spacelike region ($q^2 < 0$) the electric and magnetic form factors of the proton have been measured in elastic electron-proton scattering up to $|q^2| = 10$ (GeV/c)^2 and $|q^2| = 31$ (GeV/c)^2 respectively. Experimental results for G_M in the timelike region ($q^2 > 0$) exist for $4m_p^2 \leq s \leq 14.4$ GeV^2.

In this paper we present results from new, improved measurements of the cross section for the reaction $\overline{p}p \rightarrow e^+e^-$ in the center-of-mass (c.m.) energy interval 11.4 GeV$^2 \leq s \leq 12.4$ GeV^2. The differential cross section for this process can be expressed in terms of the proton form factors as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\overline{p}p\rightarrow e^+e^-} = \frac{\alpha^2}{4\beta_p s} \cdot \left[|G_M|^2 (1+\cos^2\theta^*) + \frac{4m_p^2}{s} |G_E|^2 \sin^2\theta^*\right] \qquad (1)$$

Where θ^* is the scattering angle of the electron in the c.m. and β_p is the velocity of the proton(antiproton) in the c.m.: $\beta_p = \sqrt{1 - 4m_p^2/s}$.

Fermilab experiment E835 is dedicated to the study of charmonium by resonant formation in $\overline{p}p$ annihilations. It is a fixed target experiment, in which the $\overline{p}$ beam circulating in the accumulator intersects a hydrogen gas jet target. It has taken data from October 1996 through September 1997 and, in a second run, from January through November 2000. The analysis reported in this paper refers to the latter data taking period.

The E835 apparatus is optimized for the detection of the electromagnetic decays of charmonium for a better signal to noise ratio. It is a non magnetic spectrometer with full azimuthal (ϕ) coverage and polar angle (θ) acceptance ranging from 2° to 70° in the lab frame. The central detector ($11^\circ < \theta < 70^\circ$) has cylindrical symmetry around the beam axis. Its main components are: the central tracking system (consisting of scintillator hodoscopes, straw chambers and a scintillating fiber tracker), a threshold Čerenkov counter for e/π discrimination and an electromagnetic calorimeter (CCAL) made of 1280 leadglass blocks pointing to the interaction region. A detailed description of the E835 detector can be found in[1].

The first level trigger for the e^+e^- final state requires the two electrons: each defined as the coincidence of the appropriate elements of H1, H2 and the corresponding cells of the Čerenkov . Independently the first level trigger requires two high-energy showers in the central calorimeter with an azimuthal opening angle greater than 90^o.

Events which satisfy the first level trigger are processed by the on-line filter, which selects events in which the two highest-energy clusters in CCAL have an invariant mass greater than 2.2 GeV/c^2.

Events are reconstructed off-line using all information from the central tracking detectors, the Čerenkov counter and the Central Calorimeter. The two electron candidates are identified as the tracks with the highest invariant mass. The selection of $\overline{p}p \to e^+e^-$ proceeds in four steps.

(a) *Electron identification.* For each candidate electron track a variable is constructed, called *Electron Weight* (EW), using the pulse heights in H1, H2, H2' and Čerenkov counter, second moments of the transverse shower distribution in CCAL and the fractional shower energy in 3×3 block region of CCAL. EW is a likelihood ratio for the electron hypothesis versus background hypothesis. Since we search events with two electrons we use the product of the two *Electron Weights*. In order to reduce the data sample size a pre-selection is applied requiring $\log_{10}(ew1 * ew2) > -1$ and an invariant mass of the two candidate electrons greater than 2.2 GeV/c^2. Only events which pass this preselection undergo the subsequent analysis. In the final selection we require $\log_{10}(ew1 * ew2) > 0$.

(b) *Fiducial volume.* To ensure homogeneity in the response of the detector we accept only events in which the two electrons have polar angles in the interval $15^o < \theta < 60^o$. This region is well covered by Central Calorimeter, Čerenkov counter and central tracking detectors.

(c) *CCAL multiplicity.* To avoid rejecting events in which the electron or positron radiates a Bremsstrahlung photon which forms a distinct cluster in the CCAL, we do not impose a strict cut demanding only two ontime clusters. Events with more than two ontime clusters are kept provided that the extra clusters, when paired with either electron candidate, give an invariant mass below 100 MeV/c^2. In addition any number of out-of-time or undetermined clusters is allowed.

(d) *Kinematical fit.* The goodness of the e^+e^- final state is finally tested by means of a four constraint kinematical fit. Since the energy range considered is near to charmonium resonances which decay into $J/\psi X$ we use also a kinematical fit to test the $J/\psi X$ final state, then we compare the fit probability for e^+e^- ($Prb(e^+e^-)$) with that for $J/\psi X$ ($Prb(J/\psi X)$). The event is accepted if $Prb(e^+e^-) > Prb(J/\psi X)$ and if $Prb(e^+e^-) > 1\%$. The number N of events selected with these criteria is shown in Table 1.

The overall efficiency of the analysis is the product of the three efficiencies corresponding to the first level trigger, the off-line preselection and the final selection.

The trigger efficiency ϵ_{trig} has been calculated from special trigger runs at the ψ' energy, which required only one electron. The trigger efficiency turns out

s (GeV^2)	L (pb^{-1})	N	σ_{acc} (pb)	$\lvert\cos\theta^*\rvert_{max}$	$10^2 \times \lvert G_M\rvert$ (a)	(b)
11.42±0.09	8.52	8	$1.59^{+0.79+0.10}_{-0.55-0.09}$	0.568	$1.72^{+0.42+0.05}_{-0.30-0.05}$	$1.92^{+0.47+0.06}_{-0.33-0.05}$
11.93±0.13	3.95	3	$1.29^{+1.25+0.08}_{-0.70-0.07}$	0.585	$1.57^{+0.76+0.05}_{-0.43-0.04}$	$1.74^{+0.85+0.05}_{-0.47-0.05}$
12.43±0.01	50.50	31	$1.04^{+0.22+0.06}_{-0.19-0.06}$	0.601	$1.43^{+0.15+0.04}_{-0.13-0.04}$	$1.58^{+0.17+0.05}_{-0.14-0.04}$
14.40±0.19	5.17	0	< 0.82	0.603	< 1.40	< 1.53
18.22±0.01	2.10	0	< 2.03	0.512	< 2.81	< 3.03

Table 1
Summary of the results of the form factor analysis. For each energy region the integrated luminosity L, the selected number of events N, the cross section $\sigma_{acc} = N/(\epsilon \cdot L)$ are reported. $|\cos\theta^*|_{max}$ is the maximum value of $|\cos\theta^*|$ where θ^* is the scattering angle in c.m.; (a) $|G_M|$ calculated in the hypothesis $|G_E| = |G_M|$; (b) $|G_M|$ calculated in the approximation of negligible electric contribution.

to be [2]:

$$\epsilon_{trig}^{data} = 0.90 \pm 0.02 \tag{2}$$

The efficiency of the preliminary selection has been calculated with four clean samples of $\psi' \to e^+e^-$ events selected requiring only two ontime CCAL clusters and applying tight topological cuts relative to the two body final state. The value of the efficiency obtained from these samples is:

$$\epsilon_{pres}^{data} = 0.966 \pm 0.013(stat)^{+0.027}_{-0.036}(syst) \tag{3}$$

To estimate the efficiency of the final selection we used a clean sample of $\psi' \to e^+e^-$ events. The efficiency of the restriction on the fiducial volume is taken into account in the integration of the differential cross section (1).

Fig.1 shows invariant mass distributions for candidate electrons after preliminary selection (a) and after final selection (b) at the ψ' formation energy. The cross-hatched areas in both histograms correspond to the background contamination in these samples, extracted applying the same analysis to the data taken off resonance at $\sqrt{s} = 3.7$ GeV. Horizontal lines correspond to the decay $\psi' \to J/\psi X$ selected requiring $Prb(J/\psi X) > 1\%$ and $Prb(e^+e^-) < 10\%$ (with an efficiency of $\sim 95\%$). It can be seen that the background contamination from J/ψ-inclusive decay is very low.

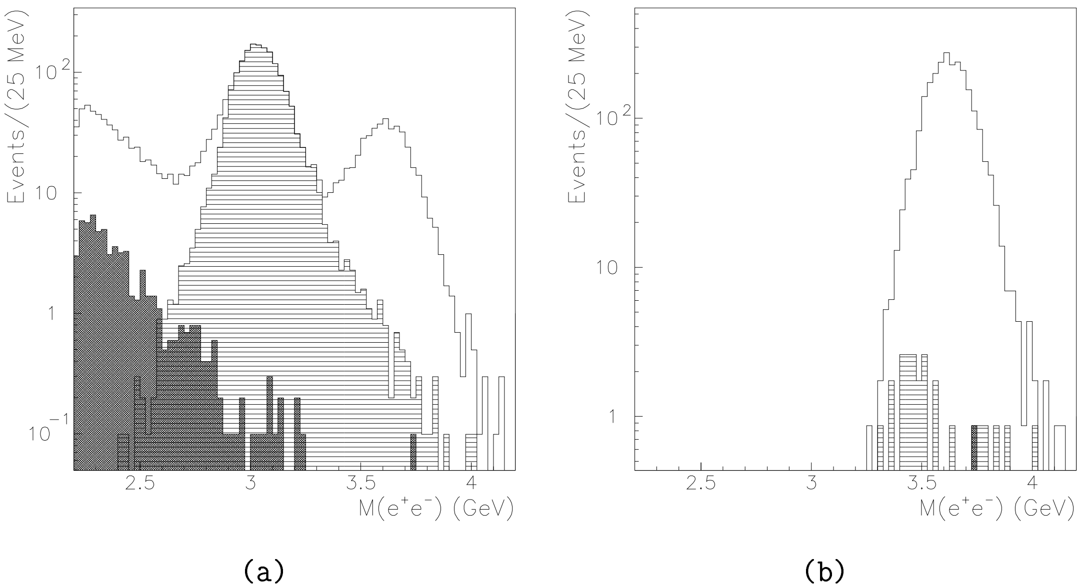

Fig. 1. Invariant mass distribution for candidate electrons after preliminary selection (a) and after final selection (b): at ψ' energy (white) and at $\sqrt{s} = 3.7$ GeV (cross-hatched); horizontal lines correspond to J/ψ-inclusive subsample at ψ' energy. (The number of events has been rescaled by luminosity).

The efficiency of the final selection is defined as the fraction of events in the preliminary sample (Fig.1(a) white) that survive all cuts (Fig.1(b) white), once background (including $J/\psi X$ events) is subtracted. We consider only events with invariant mass greater than 3.4 GeV/c^2. The efficiency of the final selection is:

$$\epsilon_{sel} = 0.679 \pm 0.009(stat)^{+0.037}_{-0.026}(syst) \tag{4}$$

The overall analysis efficiency is thus:

$$\epsilon_{ana} = 0.590 \pm 0.017(stat)^{+0.036}_{-0.032}(syst) \tag{5}$$

The main possible sources of background for the e^+e^- final state are: photon conversions and π^0 Dalitz decays, two body hadronic final states (mainly $\pi^+\pi^-$) and inclusive $J/\psi X$ events. These background processes have been studied in detail and their contributions have been estimated to be as follows [3]:

(1) Photon conversions from $\overline{p}p$ decays to $\gamma\gamma$, $\pi^o\gamma$ and $\pi^0\pi^0$ and Dalitz decays. We estimate these processes to contribute backgrounds of $< 3.1 \times 10^{-3}$ pb, $< 2.0 \times 10^{-3}$ pb and $< 1.7 \times 10^{-3}$ pb at $s = 11.42\ GeV^2$, $11.93\ GeV^2$ and $12.43\ GeV^2$ respectively.

(2) Misidentification of the $\pi^+\pi^-$ final state as e^+e^- . We estimate this process to contribute $< 4.3 \times 10^{-3}$ pb, $< 3.6 \times 10^{-3}$ pb and $< 2.9 \times 10^{-3}$ pb at $s = 11.42\ GeV^2$, $11.93\ GeV^2$ and $12.43\ GeV^2$ respectively.

(3) Inclusive final state $J/\psi X \to e^+e^-$, with X not detected. The contribution of this process is estimated to be $< 3.0 \times 10^{-2}$ pb, $< 2.3 \times 10^{-2}$ pb and $< 1.5 \times 10^{-2}$ pb at $s = 11.42\ GeV^2$, $11.93\ GeV^2$ and $12.43\ GeV^2$ respectively.

Comparing the estimated upper limits with the values of cross section reported in Tab.1 we can consider the background contamination negligible, therefore no subtraction from the number of candidate events is performed.

From the number N of selected events with an integrated luminosity L and an efficiency ϵ the differential cross section integrated in the c.m. acceptance region can be calculated as follows:

$$\sigma_{acc} = \frac{N}{\epsilon L} \tag{6}$$

σ_{acc} is a function of the magnetic and electric form factors G_M and G_E:

$$\begin{aligned} \sigma_{acc} &= \int_0^{2\pi} d\phi \int_{-|\cos\theta^*|_{max}}^{+|\cos\theta^*|_{max}} \frac{d\sigma}{d\Omega} d(\cos\theta^*) \\ &= \frac{\pi\alpha^2}{2\beta_p s} \cdot \left[A \cdot |G_M|^2 + \frac{4m_p^2}{s} \cdot B \cdot |G_E|^2 \right] \end{aligned} \tag{7}$$

where A and B are:

$$A = 2 \cdot \int_0^{+|\cos\theta^*|_{max}} (1 + \cos^2\theta^*) d(\cos\theta^*) \tag{8}$$

$$B = 2 \cdot \int_0^{+|\cos\theta^*|_{max}} (1 - \cos^2\theta^*) d(\cos\theta^*) \tag{9}$$

Since the small number of events and the limited $\cos\theta^*$ range do not allow us to measure the angular distribution, two alternative hypotheses have been made: (a) $|G_E| = |G_M|$, as at the threshold of the timelike region ($s = 4m_p^2c^4$); (b) the "electric" contribution is assumed to be negligible. Under these two hypotheses the expressions of $|G_M|$ are respectively:

$$(a) \quad |G_M| = \left[\frac{2\ \beta_p\ s\ N}{\pi\ \alpha^2\ \left[A + \frac{4m_p^2}{s} B\right]\ L\ \epsilon} \right]^{\frac{1}{2}} \tag{10}$$

$$(b) \quad |G_M| = \left[\frac{2\ \beta_p\ s\ N}{\pi\ \alpha^2\ A\ L\ \epsilon} \right]^{\frac{1}{2}} \tag{11}$$

Tab.1 shows the results for the magnetic form factor of the proton calculated with the two hypotheses. An upper limit at the 90 % confidence level is reported where there are no observed events. The errors shown are statistical and, respectively, systematic. The systematic uncertainty is due to the errors on efficiency and luminosity. The values of $|G_M|$ obtained under hypothesis

(a) are plotted in Fig. 2, where they are compared with earlier measurements. It can be seen that the new data are in excellent agreement with the previous E760 and E835 results.

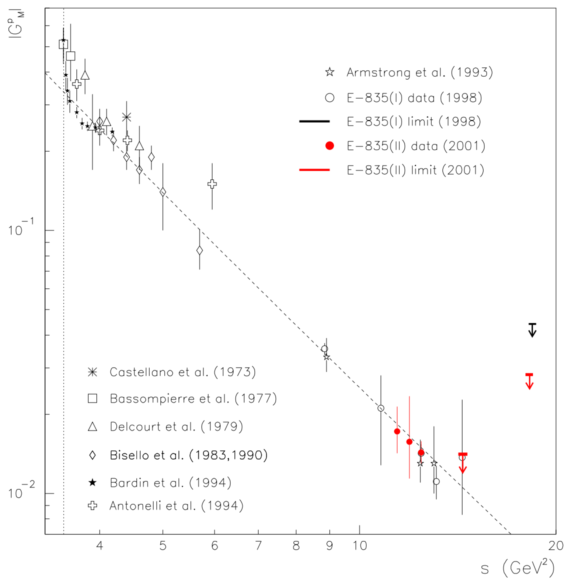

Fig. 2. All existing values of the magnetic form factor in timelike region obtained with the hypothesis $|G_M| = |G_E|$.

Quantum Chromodinamics predicts an asymptotic behavior for the magnetic form factor of the proton in the timelike region at high energy of the form:

$$G_M(Q^2) = \frac{C}{s^2} \cdot \left(\ln \frac{s}{\Lambda^2}\right)^{-2} \tag{12}$$

where $\Lambda = 0.3\ GeV$ is the QCD scale parameter and C is a free parameter. This functional form comes from the prediction that for large momentum transfers $q^4|G_M|$ should be nearly proportional to the square of the running coupling constant for strong interactions $\alpha_s^2(q^2)$ [10,11]. The dashed line in Fig. 2 shows a fit to the data according to equation (12). As can be seen, the fit agrees well with the data over the q^2 range explored so far.

In summary, we have presented new, high-precision measurements of the proton magnetic form factor in the timelike region at high q^2. The results are in excellent agreement with previous measurements and with the semi-quantitative predictions of QCD.

The authors wish to acknowledge the technical support from their respective institutions and the contribution of the Fermilab Beams Division. This research was supported by the U.S. Department of Energy and the Italian Istituto Nazionale di Fisica Nucleare.

References

[1] M. Ambrogiani et al., Phys. Rev. D **60**, 032002 (1999).

[2] W. Baldini, *The charged trigger efficiency of E835-runII.* Fermilab E-835 internal note, unpublished.

[3] M. Andreotti, *Measurements of the magnetic form factor of the proton for large timelike momentum transfers.* Fermilab E-835 internal note, unpublished.

[4] G. Stancari, *Measurements of th Magnetic Form Factor of the Proton for Large Timelike Momentum Transfers.* Doctoral Dissertation, Università degli Studi di Ferrara.

[5] T.A. Armstrong et al., Phys. Rev. Lett. **69**, 2337 (1992).

[6] T.A. Armstrong et al., Phys. Rev. D **56**, 2509 (1997).

[7] M. Ambrogiani et al., Phys. Rev. D **62**, 052002 (2000).

[8] T.Fields et al., Phys. Lett. **40B**, 503 (1972).
A.Eide et al.,Nucl. Phys. **B60**, 173 (1973).
T.Buran et al., Nucl. Phys.**B116**, 51 (1976).

[9] T.A. Armstrong et al., Phys. Rev. Lett. **70**, 1212 (1993).

[10] G. Lepage and S. Brodsky, Phys. Rev. Lett. **43**, 545 (1979).

[11] G. Lepage and S. Brodsky, Phys. Rev. D**22**, 2157 (1980).