EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE/91-30
February 11th, 1991

PRECISE DETERMINATION OF THE ELECTROMAGNETIC FORM FACTOR OF THE PROTON IN THE TIME-LIKE REGION UP TO s = 4.2 GeV²

G. Bardin[1], G. Burgun[2], R. Calabrese[3], G. Capon[4], R. Carlin[5], P. Dalpiaz[3], P.F. Dalpiaz[3], J. Derre[2], U. Dosselli[5], J. Duclos[1], J.L. Faure[2], F. Gasparini[5†], M. Huet[1], C. Kochowski[2], S. Limentani[5], E. Luppi[3], G. Marel[2], E. Mazzucato[3], E. Pauli[2], F. Petrucci[3], M. Posocco[5], M. Savrié[3], R. Stroili[5], L. Tecchio[6], C.Voci[5], N. Zekri[1].

submitted for publication to Phys.Lett.B

Abstract

The s dependence of the proton form factor in the time-like region has been determined up to s = 4.2 GeV², assuming the validity of the $|G_e| = |G_m| = |G|$ hypothesis. Data were taken in a dedicated experiment performed at the LEAR antiproton ring at CERN, increasing by one order of magnitude the available statistics on the proton form factor near threshold in the time-like region. Our results consist of cross-section measurements of the $\bar{p}p \rightarrow e^+e^-$ reaction for different beam momenta in the kinematical range $3.6 \leq s \leq 4.2$ GeV². The observed s dependence of the form factor close to threshold differs appreciably from the one suggested by previous experiments.

(1) Département de Physique Nucléaire, CEN Saclay, France (2) Département de Physique Des Particules Elémentaires, CEN Saclay, France (3) Dipartimento di Fisica dell"Università and I.N.F.N., Sez. Ferrara, Italy (4) Laboratori Nazionali dell"I.N.F.N., Frascati, Italy (5) Dipartimento di Fisica dell"Università and I.N.F.N., Sez. Padova, Italy (6) Istituto di Fisica Superiore dell"Università and I.N.F.N., Sez. Torino, Italy †Now Università di Udine

Introduction

In the electromagnetic annihilation processes:

$$\bar{p}p \rightarrow e^+e^- \quad 1)$$

$$e^+e^- \rightarrow \bar{p}p \quad 2)$$

the quadrimomentum q^2 of the exchanged photon is time-like and yields information about the electro-magnetic frequency structure of the proton. Channels 1) and 2) are therefore dominated by $J^{PC} = 1^{--}$ resonances.

The relation between electromagnetic form factors and cross section can be found in the literature [1] . In the time-like region where the existing data [2,3,4] are rather scarce and inaccurate compared with the space-like results, the form factor $|G|$ has been derived from total cross section measurements of reactions 1) and 2) with the assumption $|G_e| = |G_m| = |G|$. The large errors of the data allow a reasonable agreement with Vector Meson Dominance (VMD) model predictions[5,6,7].

Reaction 1) was investigated at the Low Energy Antiproton Ring (LEAR) at CERN with a dedicated apparatus in which the collected statistics allowed an accurate scan of the $|G|$ form factor near threshold. The experiment was performed at several incident beam momenta in order to explore the full kinematical range of the reaction from threshold ($s = 4m_p^2$) up to $s = 4.2$ GeV^2. The results obtained from the 300 MeV/c beam setting have already been published [8]. In this paper are presented the data concerning $\bar{p}$ beam momentum ranging from 540 MeV/c to 900 MeV/c .

With a total of about 4×10^{12} $\bar{p}$ impinging on a liquid hydrogen target, more than 1000 e^+e^- events produced in-flight by reaction 1) were recorded, improving by one order of magnitude the amount of data available on the proton form factor in the time-like region.

The experimental set-up and its performances

The experimental apparatus is fully described elsewhere [9]. Here we summarize its main features. Accepting a rate of $2.10^6 \bar{p}$/sec in a 30 cm long, 6 cm diameter liquid hydrogen target, the apparatus ensured the requested high luminosity. The momentum for the outcoming particles was measured by a central detector surrounding the target and located in the gap of a C-magnet, 1m in diameter and 40 cm high. The geometrical acceptance of the magnetic field was $0.8 \times 360^\circ$ in the horizontal plane and $\pm 20^0$ in the vertical one. The momentum resolution was further improved by a double layer of drift tubes situated at about 1.5 meter from the center of the system. The discrimination of e^+e^- events from the overwhelming hadronic background due to $\bar{p}$ annihilating into pions and kaons was achieved using a ring of gas Cerenkov counters filled with isobutane at atmospheric pressure and a ring of shower detectors, 5.5 radiation length thick, made of lead plates interleaved with limited streamer tubes. The rejection of $\bar{p}p \rightarrow h^+h^-$ events was about 10^4 at the trigger level and up to 10^7 after the off-line analysis. The overall acceptance (solid angle times efficiency) of the apparatus for e^+e^- events was about 7% . A selective trigger based upon the two-body kinematics was obtained from two layers of concentric hodoscopes made of scintillation counters. Most of the 2-body events correspond to the hadronic annihilation $\bar{p}p \rightarrow h^+h^-$ where h^+h^- stands for $\pi^+\pi^-$ and K^+K^-. A small fraction of such events was recorded for continuous monitoring and normalization purposes, essential to this experiment. The good momentum resolution of the spectrometer ($\Delta p/p \approx 2\%$) provided a clean separation between kaons and pions [9].

Data analysis

The results have been obtained at various beam momentum settings ranging from 540 MeV/c to 900 MeV/c, as reported in the first column of Table 1, while the mean incident momentum values are in column 2. The corresponding numbers of $\bar{p}$ impinging on the target are reported in column 3.

The cross section $\sigma(\bar{p}p \rightarrow e^+e^-)$, has been evaluated on the basis of the number of events of reaction 1), selected with the criteria underlined below.

The reconstructed vertex of the e^+e^- pair was requested to be inside the target volume. Cuts were applied, in the center of mass system, on the momenta of the particles and on their opening angle. As an example, we show in fig. 1 the e^+e^- opening angle distribution in the center of mass system for the 600 MeV/c beam momentum setting. The background contribution coming from multi-body events is rather flat and corresponds to less than 10% of the signal in the region of the peak for the two-body annihilation events.

The rejection of the hadronic events in the e^+e^- candidates sample is based on cuts applied on the Cerenkov amplitudes and the number of hits in the shower detector as defined in [8]. Within these cuts, the remaining background, about 5% of the e^+e^- events, has been subtracted to get the corrected numbers $N_{e^+e^-}$ of e^+e^- events which are reported in Table 1,column 4. A fraction of the hadron pairs was recorded and analyzed with the same kinematical criteria as the lepton ones, but without the Cerenkov signal and the shower type response of the shower detector. The corresponding selected number $N_{h^+h^-}$ of h^+h^- pairs is given in the 5th column of Table 1. The demultiplication factor applied to the hadronic trigger is 1000 at 540 and 900 MeV/c, 791 at 600 MeV/c and 678 at 700 MeV/c

The relative efficiency for detecting hadron against lepton pairs, $\epsilon(\frac{h^+h^-}{e^+e^-})$, has been provided at each beam energy by a Monte Carlo simulation and is given in column 6. All the numbers are evaluated in the range -0.8 $\leq$ cos θ_{cm} $\leq$ 0.8. For the 900 MeV/c sample, these limits are -0.7 $\leq$ cos θ_{cm} $\leq$ 0.9. The center of mass angular distributions of the outcoming h^+h^- obtained at various energies are compatible with the existing data [10], as it can be seen in fig 2a, where this distribution is presented for the 600 MeV/c beam momentum setting. The corresponding angular distribution of the $\bar{p}p \rightarrow e^+e^-$ sample is shown in fig 2b.In the angular $|cos(\theta_{cm})|$ range defined above the data are compatible with the $|G_e| = |G_m|$ hypothesis.

The hadronic cross section $\sigma(\bar{p}p \rightarrow h^+h^-)$ at the various beam momenta is deduced from literature [10].Because of some incompatibilities among the various published data, only the most recent and accurate have been chosen for the $\bar{p}p \rightarrow \pi^+\pi^-$, K^+K^- total [10e,i] and differential [10e,f,g,i] cross sections. A polynomial fit on this data in the same angular $|cos(\theta_{cm})|$ range as in this analysis, has provided the energy behaviour of the h^+h^- cross section necessary for our normalization. The values obtained by this procedure are reported in column 8 of the Table 1. The $\sigma(e^+e^-)$ cross section has been evaluated by comparing number of events $N_{e^+e^-}$ to $N_{h^+h^-}$, taking into account the radiative and coulomb correction factor δ [8,11] according to the relation :

$$\sigma(\bar{p}p \rightarrow e^+e^-) = \frac{N_{e^+e^-}}{N^*_{h^+h^-}} \epsilon(\frac{h^+h^-}{e^+e^-}) \sigma(\bar{p}p \rightarrow h^+h^-) \delta \qquad 3)$$

in which the number $N^{*}_{\lambda^{+}\lambda^{-}}$ includes the correction due to the demagnification of the hadron trigger. The radiative corrections are of the order of 8% while the coulomb corrections vary from 4% at 540 MeV/c to 1% at 900 MeV/c.

The inefficiencies of the apparatus due to the variation of the high $\bar{p}$ beam rate have been determined by analyzing "minimum bias trigger" events recorded only with the requirement of a signal in the beam hodoscope. An independent normalisation based on the number of incident $\bar{p}$ gives compatible results.

The obtained cross sections values are reported in column 9 of Table 1.

In the hypothesis of $|G_e| = |G_m| = |G|$ the form factor $|G|$ is related to the differential cross section by the equation:

$$\frac{d\sigma}{d\cos\theta_{cm}} = \frac{\pi}{4}\frac{\alpha^2}{p_{cm}s^{\frac{1}{2}}}|G|^2(s+4M^2)(1+\frac{s-4M^2}{s+4M^2}cos^2(\theta_{cm})) \qquad 4)$$

where p_{cm} is the incoming momentum in the center of mass system, s the total energy squared, α is the fine structure constant and M the proton mass. By integrating 4) over our selected range, we obtain the final values of $|G|$ for the different energies (see the last column of Table 1).

Discussion of the results

The values of $|G|$ reported in Table 1 at different s are presented in fig 3, (full circles),together with the the results of previous experiments with lower statistics. The data from threshold up to s = 3.59 GeV^2 have already been published [8]. Our results outline a steep slope near threshold, while the distribution at higher energy is almost flat. Although the previous low statistics measurements are compatible with our result, the physical meaning of the new data seems completely different. The VMD model as presented in ref. [7], for instance,which fits well the previous points, does not reproduce our data.

Aknowledgements

We thank doctor Mark Schneegans, for his important contribution to the proposal of this experiment. We are indebted with all the staff of LEAR of CERN for the careful and intelligent work to run the accelerator. We are grateful to Dr. Mazzone and Mr. Bouchaton for the preparation and running of the hydrogen target. We also thank all our technicians in particular, Mr. J.M. Anfreville, Y.Baillon, A.

Galvani, V. Chiaratti, S. Bigoni,G. Bonora, J.M.Garin, D.Gautherau, R.Giantin, H.Martin, M.Milisic, A. Mougeot, G.Pitacco, L. Sorrentino, J.Tartas, J.Thinel and L. Tracchi, for all the work needed to prepare the spectrometer. We all appreciated the work of Dr G.Poletti, in the tape handling and analysis.

references

[1] A.Zichichi et al., Il Nuovo Cimento **24** (1962)170
M.Gourdin, Physics Report (Section C of Physics Letters) **11** (1974)29

[2] M.Castellano et al., Il Nuovo Cimento A **14** (1973)1

[3] G.Bassompierre et al., Physics Letters B **64** (1976)475
G.Bassompierre et al., Physics Letters B **68** (1977)477
G.Bassompierre et al. Il Nuovo Cimento A **73** (1983)347

[4] B.Delcourt et al., Physics Letters B **86** (1979)395
D.Bisello et al., Nuclear Physics B **224** (1983)379
D.Bisello et al., Zeitschrift fur Physik C, Particles and Fields **48** (1990)23

[5] T.Massam and A.Zichichi, Il Nuovo Cimento **43** (1966)1137

[6] J.G.Korner et al., Phys. Rev. D **16** (1977)2165
P.Cesselli et al., Physics at Lear with Low Energy Cooled Antiproton
Edited by Gastaldi and Klapish, Plenum Press (1984)355

[7] S.Dubnicka, Il Nuovo Cimento A **103** (1990)1417

[8] G.Bardin et al., Measurement of the proton electromagnetic form factor near threshold in the time-like region
To be published in Physics Letters B

[9] G.Bardin et al., Nucl.Instr.Meth. A **259** (1987)376

[10] a) R.Bizzari et al., Lettere al Nuovo Cimento **1** (1969)749
b) H.Nicholson et al., Phys. Rev. Lett. **23** (1969)603
c) A.Mandelkern et al., Phys. Rev. D **4** (1971)2658
d) H.Nicholson et al., Phys. Rev. D **7** (1973)2572
e) E.Eisenhandler et al., Nuclear Physics B **96** (1975)109
f) F.Sai et al., Nuclear Physics B **213** (1983)371
g) T.Tanimori et al., Phys. Rev. Lett. **55** (1985)1835
and Ph. D. Thesis
h) G.Bardin et al., Physics Letters B **192** (1987)471
i) Y.Sugimoto, Phys. Rev. D **37** (1988)583

[11] G.Bonneau and F.Martin, Nuclear Physics B **27**(1987)381

Table 1

Beam MeV/c (1)	P_{lab} MeV/c (2)	$10^{11}\bar{p}$ flux (3)	N_{e+e-} (4)	N_{h+h-} (5)	$\epsilon(h/e)$ (6)	$< s >$ GeV^2 (7)	$\sigma(h^+h^-)$ 10^{-30} cm^2 (8)	$\sigma(e^+e^-)$ 10^{-33} cm^2 (9)	$\|G\|$ (10)
540	505	6.56	303$\pm$20	19206$\pm$1222	1.29	3.76	390.6$\pm$ 4.2	7.3$\pm$0.8	0.262$\pm$0.014
600	581	6.25	282$\pm$21	24416$\pm$324	1.25	3.83	353.2$\pm$4.2	5.9$\pm$0.5	0.253$\pm$0.010
700	681	5.75	199$\pm$16	23900$\pm$1049	1.29	3.94	331.4$\pm$4.7	4.8$\pm$0.5	0.247$\pm$0.014
900	888	20.16	497$\pm$27	49252$\pm$2086	1.29	4.18	310.9$\pm$6.0	3.7$\pm$0.3	0.252$\pm$0.011

Figure Captions

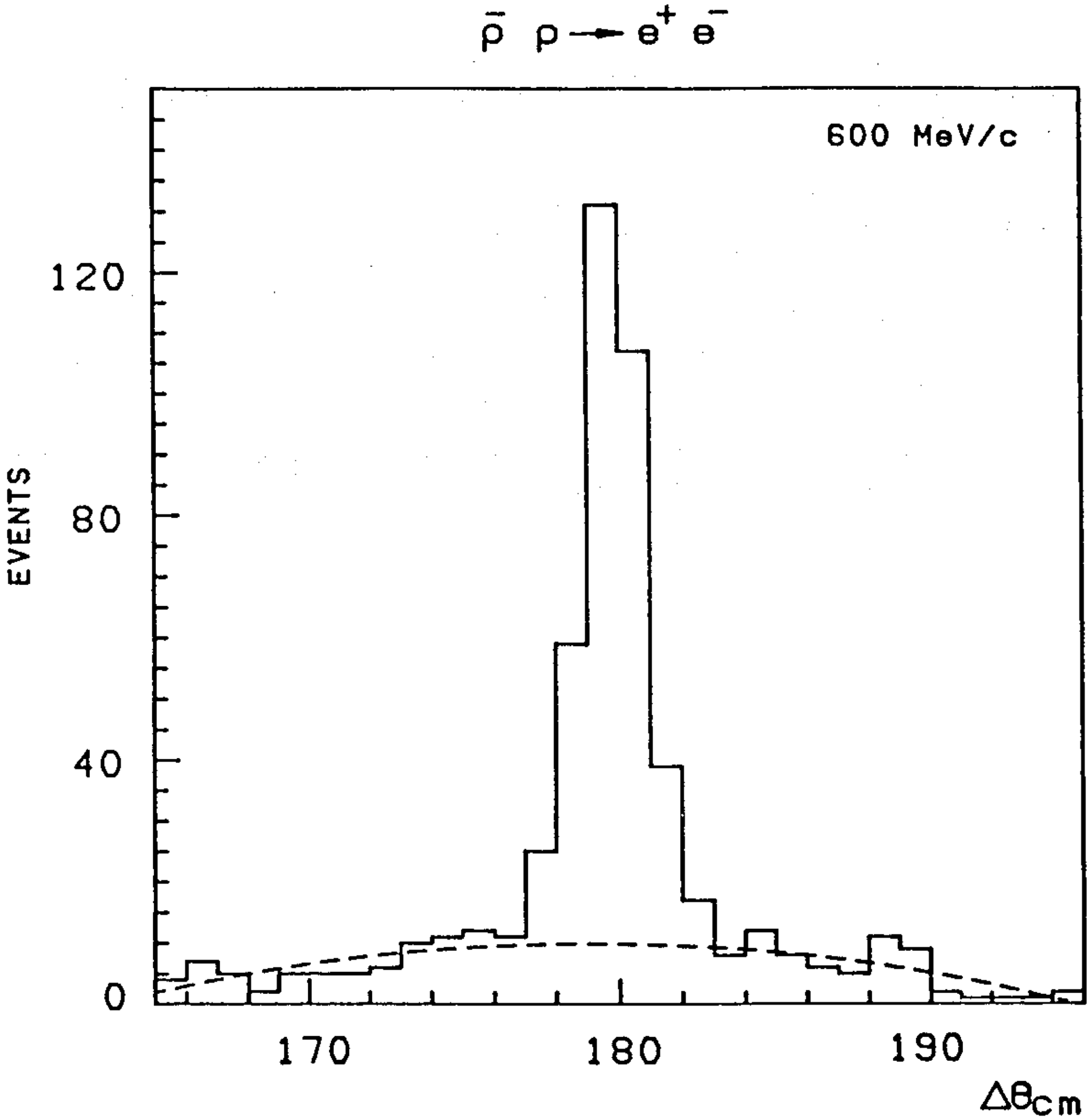
Fig. 1 - Opening angle in center of mass system for e^+e^- pairs for the 600 MeV/c beam momentum setting. The dashed line corresponds to the background contribution.

Fig. 2 - For the 600 MeV/c beam momentum:

a) Angular distribution in the c.m. system vs. $cos(\theta_{cm})$ for h^+h^- pairs ($\pi^+\pi^-$ and K^+K^-), where θ_{cm} is the angle between the directions of the incoming $\bar{p}$ and the outcoming negative particle. The curve is obtained from a smoothing of published data (see text).

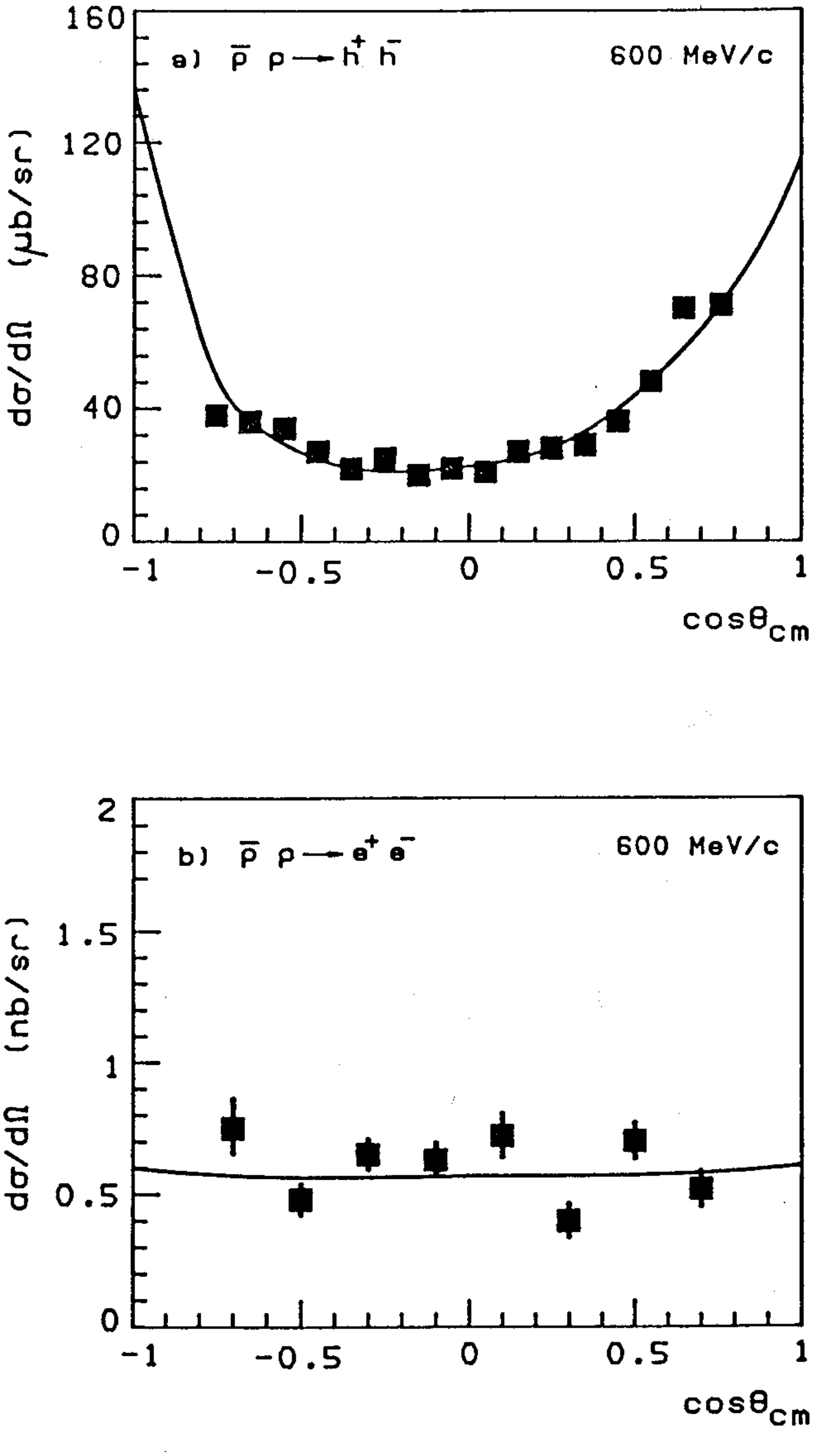
b) Angular distribution in the c.m. system vs. $cos(\theta_{cm})$ for e^+e^- pairs. The curve corresponds to the $|G_e| = |G_m|$ hypothesis.

Fig. 3 - The proton electromagnetic form factor $|G|$ as a function of s. The continuous lines are the VMD previsions for $|G_e|$ and $|G_m|$ by Dubnicka [7].



$\bar{p}\ p \to e^+ e^-$
600 MeV/c
EVENTS
120
80
40
0
170
180
190
$\Delta\theta_{cm}$

Fig.1



160
120
80
40
0
a) $\bar{p}\,p \to h^+ h^-$
600 MeV/c
dσ/dΩ (μb/sr)
-1
-0.5
0
0.5
1
cosθcm
2
1.5
1
0.5
0
b) $\bar{p}\,p \to e^+ e^-$
600 MeV/c
dσ/dΩ (nb/sr)
-1
-0.5
0
0.5
1
cosθcm

Fig.2

PROTON ELECTROMAGNETIC FORM FACTOR

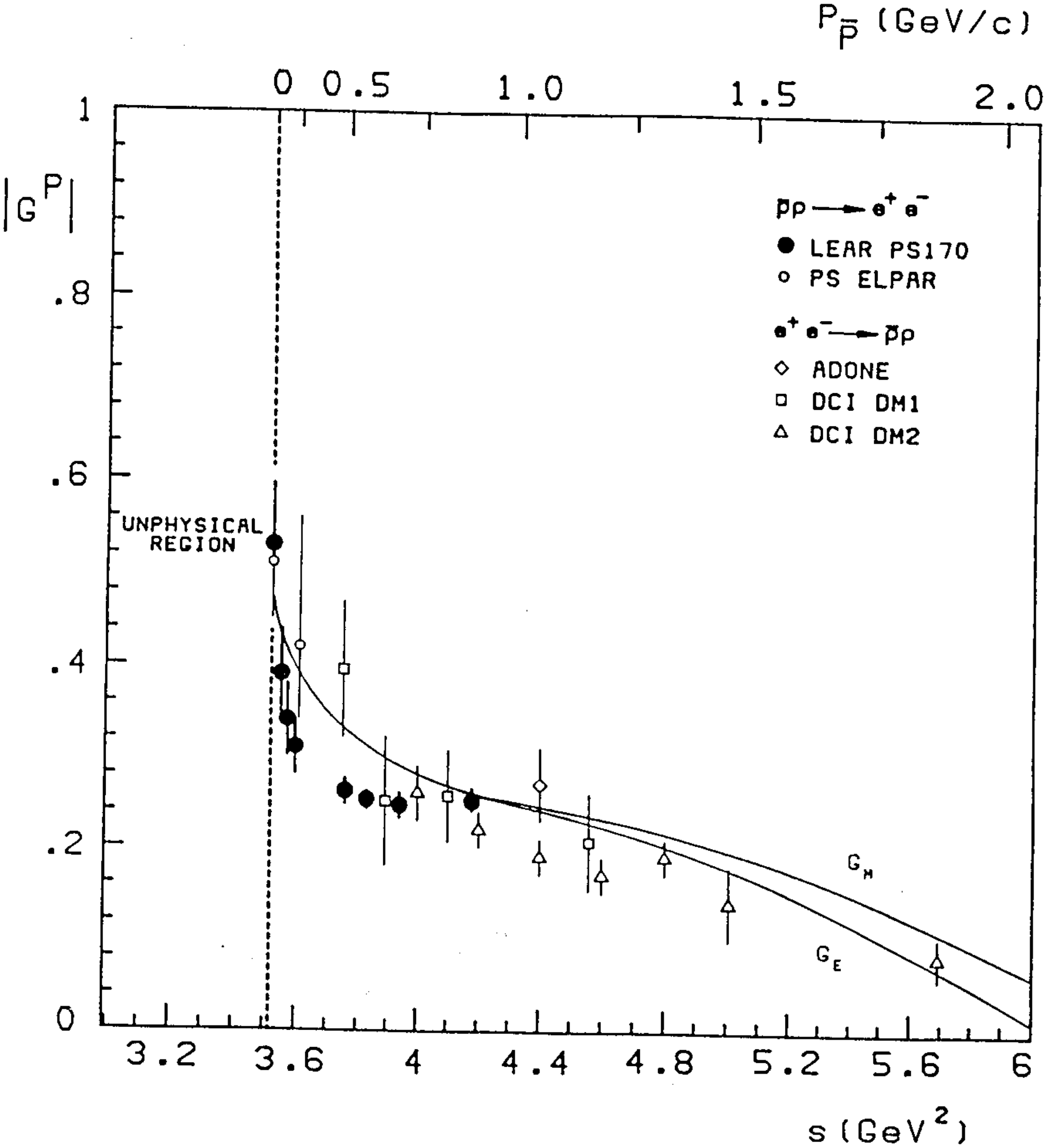


Fig.3