

FIRST DETERMINATION OF THE PROTON ELECTROMAGNETIC FORM FACTORS
AT THE THRESHOLD OF THE TIME-LIKE REGION

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ABSTRACT

From the measurement of

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

obtained in an experiment at CERN with antiprotons at rest, a value of the proton electromagnetic form factors at the threshold of the time-like region is derived:

$$G_E = G_M = 0.51 \pm 0.08 \text{ at } q^2 = -3.52 \text{ (GeV/c)}^2.$$

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1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that proper record-keeping is essential for transparency and accountability, particularly in financial matters. This section also touches upon the legal implications of failing to maintain such records, which can lead to severe consequences for individuals and organizations alike.

2. The second part of the document delves into the specific requirements for record-keeping, including the types of documents that must be retained and the duration for which they should be kept. It provides a detailed overview of the various categories of records, such as financial statements, contracts, and correspondence, and outlines the best practices for organizing and storing these documents to ensure they are easily accessible when needed.

3. The third part of the document addresses the challenges associated with record-keeping, such as the volume of data generated and the risk of data loss or corruption. It offers practical solutions and strategies to overcome these challenges, including the use of secure digital storage systems and regular data backups. Additionally, it discusses the importance of implementing robust access controls to protect sensitive information from unauthorized access.

4. The fourth part of the document focuses on the role of record-keeping in compliance with various regulations and standards. It highlights the need for organizations to stay up-to-date with the latest regulatory requirements and to ensure that their record-keeping practices align with these standards. This section also provides guidance on how to conduct regular audits to verify the accuracy and integrity of the records.

5. The fifth and final part of the document concludes by summarizing the key points discussed throughout the document. It reiterates the importance of record-keeping as a fundamental aspect of good governance and operational efficiency. It encourages organizations to adopt a proactive approach to record-keeping, ensuring that they are always prepared to meet their legal and regulatory obligations.

The knowledge of the proton electromagnetic form factors $F_{1,2}(q^2)$ is fundamental to the understanding of the structure of this particle. Several models [1] attempted to fit the numerous data in the space-like region, without any constraint in the time-like region, where the existing measurements were extremely poor. However, data in the latter region are most essential to determine the analytic function $F(q^2)$ in the whole complex plane [2].

Attempts to measure the proton form factors in the time-like region started about 15 years ago, just after precise measurements [3] were obtained in the space-like region. Experiments at CERN [4] and BNL [5] gave only upper limits at $q^2 = -6.8, -6.6$ and -5.1 $(\text{GeV}/c)^2$. The first positive result was obtained in 1972 from an e^+e^- colliding beam experiment in Frascati [6]. On the basis of 27 events, the authors evaluated $G = 0.27 \pm 0.04$ at $q^2 = -4.3$ $(\text{GeV}/c)^2$ with the hypothesis $|G_E| = |G_M| = G$.

We give here the first evaluation of the proton electromagnetic form factors at the threshold of the time-like region, at $q^2 = -3.52$ $(\text{GeV}/c)^2$, and at a near value: $q^2 = -3.61$ $(\text{GeV}/c)^2$. These results were obtained from the analysis of our data on the process:



with \bar{p} brought to rest. The reasons for studying process (1) at rest are twofold:

- i) at $q^2 = -4M_p^2$, we have strictly $G_E = G_M = G$ with G real, thus allowing an unambiguous determination of G ;
- ii) furthermore, such an experiment is complementary to any e^+e^- colliding beam experiment which could not attempt measurements below $|q^2| \sim 4$ $(\text{GeV}/c)^2$.

To allow the determination of G , the branching ratio:

$$B_{e^+e^-} = \frac{\Gamma(\bar{p}p \rightarrow e^+e^-)}{\Gamma(\bar{p}p \rightarrow \text{total})}$$

is needed. It was measured by our group in an experiment where antiprotons were stopped in a liquid hydrogen target surrounded by electron detectors [7]. These detectors, consisting essentially of scintillation counters and optical spark chambers,

allow the detection of electrons in a high hadronic background and the measurement of their direction and energy. Twenty-nine collinear pairs were found which can be attributed to reaction (1), yielding

$$B_{e^+e^-} = (3.2 \pm 0.9) \times 10^{-7} .$$

Contamination by accidental background was evaluated and found to be negligible.

Five more events can be attributed to reaction (1) in flight, where the anti-proton momentum lies between 150 and 500 MeV/c with an average value of (300 ± 20) MeV/c. Normalizing to the rate of the reaction:

$$\bar{p}p \rightarrow h^+h^-, \quad \text{where } h^+h^- = \pi^+\pi^- \text{ or } K^+K^- ,$$

observed [8] in the same apparatus and in the same momentum interval, we obtain

$$\frac{\Gamma(\bar{p}p \rightarrow e^+e^-)}{\Gamma(\bar{p}p \rightarrow h^+h^-)} = \left(\begin{array}{cc} 0.40 & +0.25 \\ & -0.16 \end{array} \right) \times 10^{-4} ,$$

on the hypothesis of equal angular distributions of the two electrons and of the two hadrons from $\bar{p}p$ annihilations at this energy.

Using the cross-section $\sigma(\bar{p}p \rightarrow h^+h^-)$ at 300 MeV/c also measured in our apparatus [9]:

$$\sigma_{h^+h^-}(300 \text{ MeV/c}) = 1.25 \pm 0.2 \text{ mb} ,$$

we derive

$$\sigma_{e^+e^-} = \left(\begin{array}{cc} 50 & +32 \\ & -20 \end{array} \right) \text{nb} .$$

At 300 MeV/c, G can be readily obtained if we assume $|G_E| = |G_M| = G$. In fact, we have

$$G = \frac{1}{\alpha} \sqrt{\frac{m \times p_{\bar{p}} \times \sigma_{e^+e^-}}{\pi}}$$

$$G = 0.46 \begin{array}{c} +0.15 \\ -0.09 \end{array} .$$

At rest, we have to use a different method to evaluate G . We can

determine $\sigma_{\text{tot}} \times p_{\bar{p}}$ at rest by extrapolation of the known measurements of σ_{tot} between 0.3 and 1 GeV/c. Figure 1 shows these data together with the best linear fit ($X^2/n_D \approx 1.6$). If we assume that the behaviour of $\sigma_{\text{tot}} \times p_{\bar{p}}$ remains linear when the antiproton momentum goes to zero, we obtain:

$$\lim_{p_{\bar{p}} \rightarrow 0} (\sigma_{\text{tot}} \times p_{\bar{p}}) = (56 \pm 2) \text{mb} \times \text{GeV}/c .$$

Using our measurement of $B_{e^+e^-}$ [7], we derive $\sigma_{e^+e^-} \times p_{\bar{p}}$. Thus

$$G_E = G_M = G = 0.51 \pm 0.08 .$$

Our values of G near and at threshold are shown in Fig. 2, together with the e^+e^- colliding beam measurement [6], the CERN [4] and BNL [5] limits and the data in the space-like region [3]. The continuous line represents a tentative fit to the experimental points in the space-like and in the time-like regions. We used the formalism of Blatnik and Zovko [1] based on the VDM model with three isoscalar (ω, ω', ϕ) poles, three isovector $(\rho, \rho'_{1250}, \rho''_{1600})$ poles and asymptotic constraints on G . More details on this fit and its significance can be found in another paper [10].

Attempts to fit all the data without heavy vector mesons did not succeed. In particular, a dipole fit (dashed line in the time-like region) with

$$G_D(q^2) = (1 + q^2/m^2)^{-2}, \quad m^2 = 0.71 \text{ GeV}^2$$

is away from the data by an order of magnitude in the time-like region.

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Figure captions

Fig. 1 : Linear extrapolation to $p_{\bar{p}} = 0$ of the known data in $\sigma(\bar{p}p \rightarrow \text{total}) \times p_{\bar{p}}$.

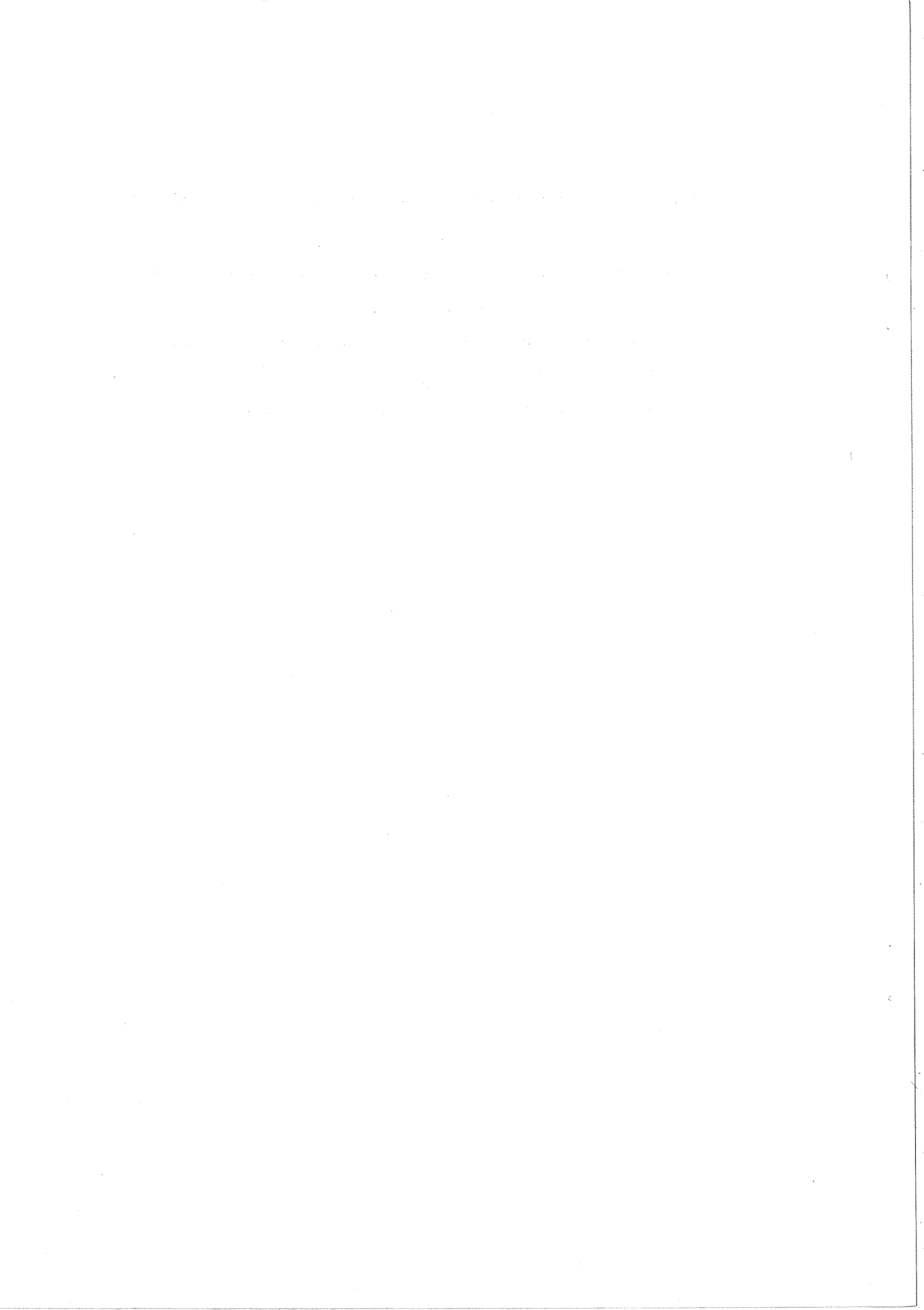
Fig. 2 : Present situation of the data on G_E for $-8(\text{GeV}/c)^2 < q^2 < 8(\text{GeV}/c)^2$.

The solid line represents a fit to the existing data, based on the VDM model with the contribution of $\omega, \omega', \phi, \rho, \rho'_{1250}, \rho''_{1600}$ mesons.

An increased statistical weight was given to the time-like data.

A dipole fit (dashed line) with $G_D(q^2) = [1 + q^2/m^2]^{-2}$, $m^2 = 0.71 \text{ GeV}^2$,

is also shown. For $q^2 > 0$, it is superposed on the solid curve.



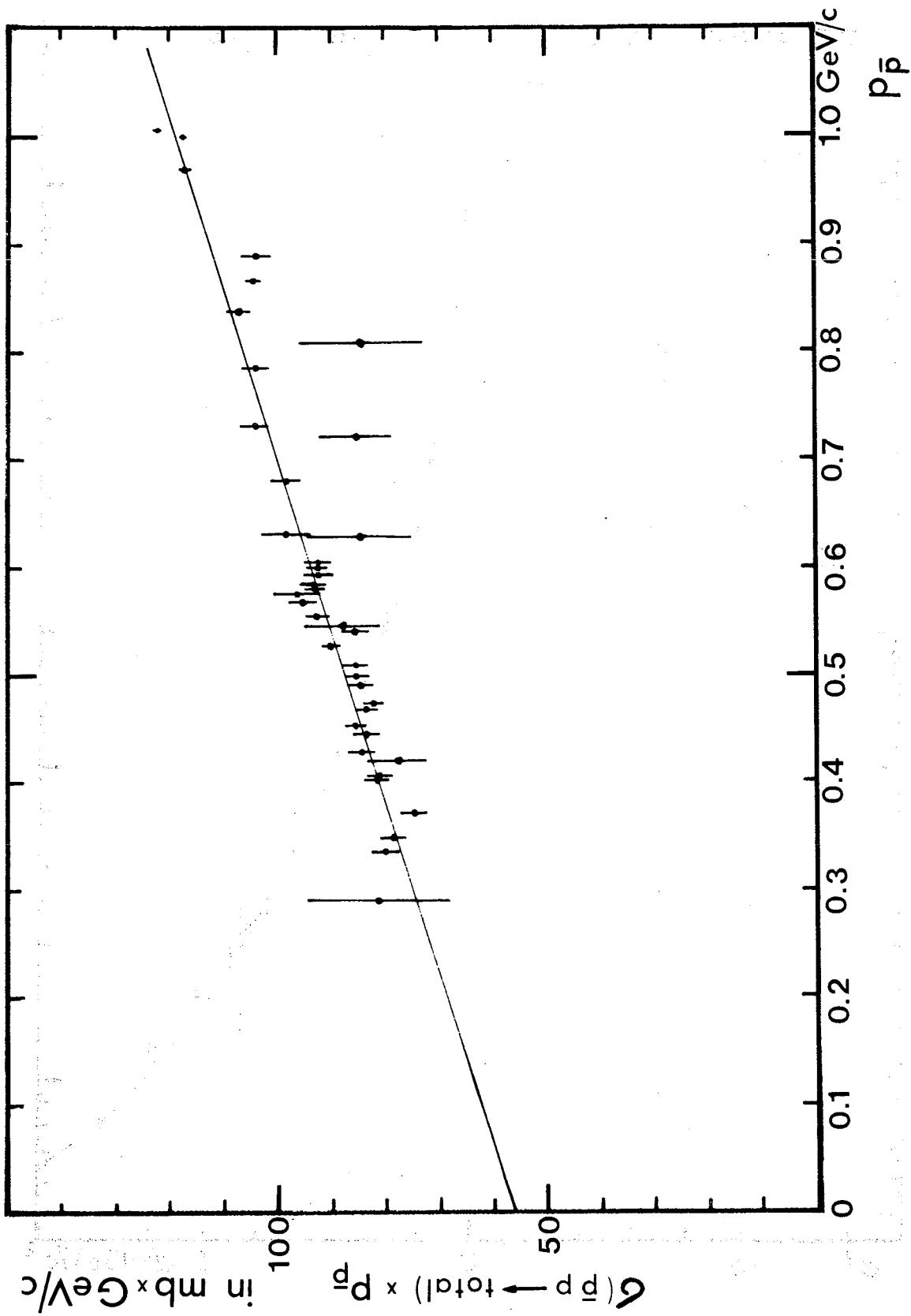


Fig. 1

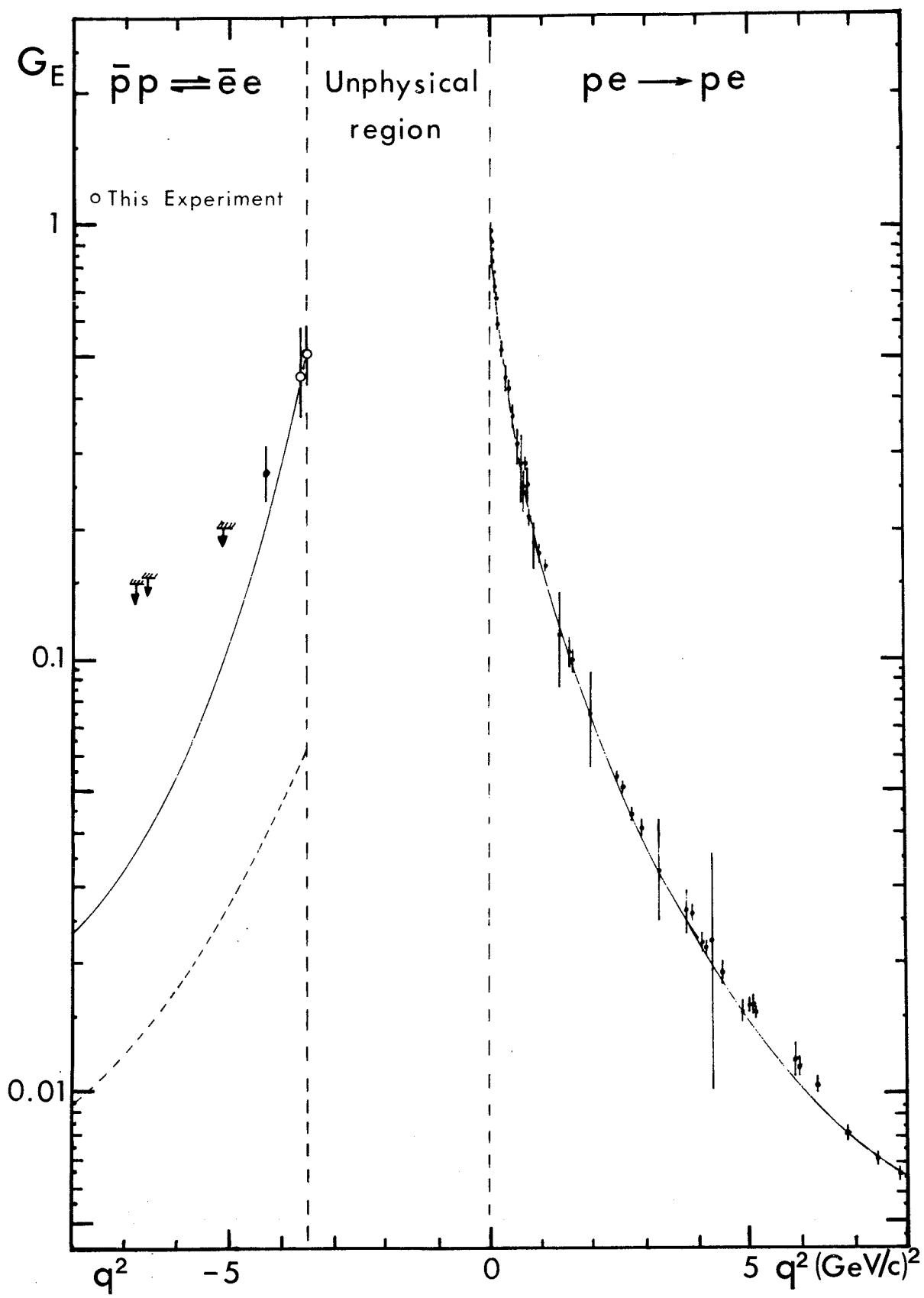


Fig. 2