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Feasibility study: proton time-like electromagnetic form factors with the $\overline{\text{P}}$ANDA experiment

Dmitry Khaneft[*†]
Helmholtz Institute Mainz, Germany
E-mail: dkhaneft@kph.uni-mainz.de

Perspectives of measuring the proton electromagnetic form factors in the time-like region at FAIR with the $\overline{\text{P}}$ANDA detector are presented. A number of simulations with $\overline{\text{P}}$ANDAroot framework on the signal $\bar{p}p \to e^+e^-$ efficiency as well as background $\bar{p}p \to \pi^+\pi^-$ rejection have been performed. Preliminary results of the simulation show that the form factors cab be measured with an unprecedented precision.

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*Speaker.

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1. Introduction

The electric G_E and magnetic G_M form factors (FFs) were introduced[1] as a linear combinations of Dirac's and Pauli's FFs. They are expressed in terms of F_1 and F_2 as:

$$G_E = F_1 - \tau F_2,\ G_M = F_1 + F_2,\ \tau = -q^2/4M^2, \tag{1.1}$$

where M is the proton mass. The electromagnetic FFs of the proton[2] provide fundamental information on the hadron structure and internal dynamics. A lot of data have been accumulated in the space-like region using elastic electron scattering. At the same time only few experiments worked in the time-like region and the obtained data do not provide with enough statistics for precision measurements. Fig. 1 summarizes world data on proton space-like and time-like form factors.

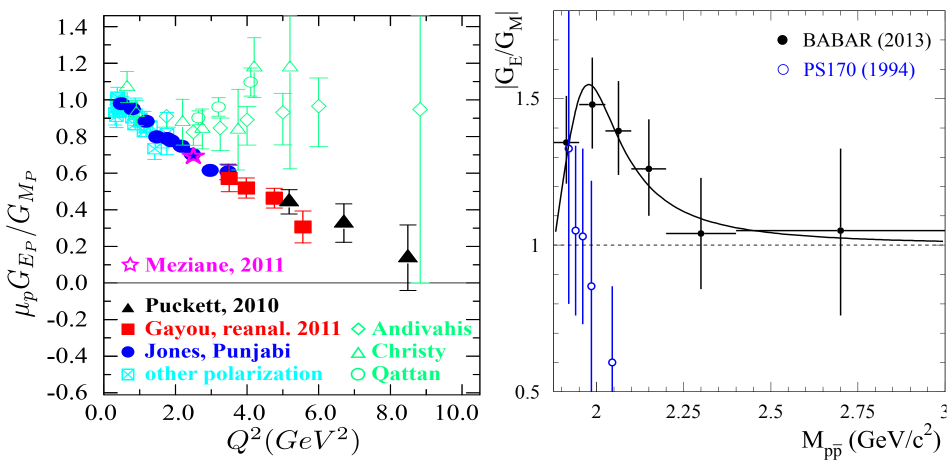

Figure 1: Left side: world data obtained for the space-like form factors by various experiments. Right side: the measured $|G_E/G_M|$ mass dependence. Filled circles depict BABAR[3] data. Open circles show PS170[4] data.

2. The $\overline{\text{P}}$ANDA experiment

The $\overline{\text{P}}$ANDA[5] experiment at FAIR[6] offers a possibility to investigate the proton time-like form factors with an unprecedented precision and in an extended kinematical region. The $\overline{\text{P}}$ANDA detector covers almost 4π of a solid angle. It will have good tracking and particle identification (PID) capabilities. All together it should provide an efficient event selection and a background suppression.

The analysis presented in this work is based on the particle identification (PID) algorithms which make use of physical quantities given by different detectors and kinematic constraints.

3. Feasibility of measuring the proton form factors with $\bar{p}p \to e^+e^-$

The differential cross section for $\bar{p}p \to e^+e^-$[7] is, in the one photon exchange approximation,

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha_e^2}{8M^2\tau\sqrt{\tau(\tau-1)}}[|G_M|^2(1+\cos^2\theta) + \frac{|G_E|^2}{\tau}(1-\cos^2\theta)], \tag{3.1}$$

where $\tau = q^2/4m_p^2$. Form factors can be determined by measuring the angular distribution of the one of charged leptons by means of Rosenbluth separation. Luminosity is a critical parameter as its precise measurement will allow for an independent extraction of G_E and G_M, otherwise only the ratio G_E/G_M can be measured.

The main difficulty is the hadron background, especially $\bar{p}p \to \pi^+\pi^-$ whose total cross section is estimated to be of the order of 10^6 times higher then the cross section of the signal [8–12]. In addition it contains the same number of particles with the same charges as the signal channel. Thus, a suppression factor of 10^8 is needed in order to ensure that the background contamination is below 1%.

Similar feasibility study was performed[13] and this work aims to improve its results by using an official simulation $\overline{\text{P}}$ANDAroot framework. The advantage of it are the more detailed and realistic detector description as well as better particle identification algorithms. The simulation consist of two step. The first one is the generation of a chosen final state and propagation of the particles through the detector. The second step is a reconstruction of physical quantities given by different detectors comprising the $\overline{\text{P}}$ANDA experiment.

The event generators for both the signal channel $\bar{p}p \to e^+e^-$ and the background channel $\bar{p}p \to \pi^+\pi^-$ were developed in Mainz. The event generator for the signal follows the cross section (Eq. 3.1) and includes radiative corrections provided by the PHOTOS[14] package. The background event generator uses parameterization based on experimental data or on the theory prediction depending on the energy range.

3.1 Background suppression and signal efficiency

In order to prove that the background can be successfully suppressed a set of simulations were performed. Three beam momenta ($p(\bar{p}) = 1.7,\ 3.3,\ 6.4 GeV/c$) were chosen and 10^8 events were generated for each of them. Using information such as momentum of a particle, energy deposit, vertex position, etc., given by detectors a selection procedure was developed. In addition, a set of kinematic cuts were applied, e.g. a requirement of the final state particles to fly in the opposite directions in the CM frame.

To study the signal efficiency another set of simulations, using $\bar{p}p \to e^+e^-$ event generator, were performed. The same selection algorithm as for the background suppression were applied. Table 1 shows a percentage of events that satisfy selection procedure for the lepton signal and the pion background. It is shown that the criteria presented above provide the background suppression factor of at least $0.7 * 10^{-8}$ $(CL = 95\%)$ what leads to the level of the background contamination below 1%.

3.2 Extraction of the proton form factors

The cross section σ of the signal channel and the number of events N were calculated using Eq. 3.1 and taking the value of the expected integrated luminosity of $\mathscr{L} = 2 fb^{-1}$. $|G_M|$ was parameterized by the Eq. 3.2[15]. As the parameterization assumes that $|G_E/G_M| = 1$ the same hypothesis was taken in this work.

$$|G_M| = \frac{22.5}{(1+q^2/0.71)^2(1+q^2/3.6)}. \tag{3.2}$$

$p_{beam}[GeV/c]$	$q^2[GeV/c]^2$	$Eff(e^+e^-)$	$\pi^+\pi^-$
1.7	5.4	31.9%	0.0%
2.78	7.27	32.8%	–
3.3	8.21	31.4%	0.0%
4.9	11.0	26.2%	–
5.9	12.9	23.1%	–
6.4	13.8	21.7%	0.0%
7.9	16.7	17.8%	–

Table 1: Percentage of events that satisfy selection procedure for the lepton signal and the pion background

$p_{beam}[GeV/c]$	$q^2[GeV/c]^2$	σ $[pb]$	N
1.7	5.4	531.0	$1.1 \cdot 10^6$
2.78	7.27	72.1	$1.4 \cdot 10^5$
3.3	8.21	32.4	$6.4 \cdot 10^4$
4.9	11.0	4.3	$9.1 \cdot 10^3$
5.9	12.9	1.5	$3.2 \cdot 10^3$
6.4	13.8	0.97	$2 \cdot 10^3$
7.9	16.7	0.29	580

Table 2: Cross section σ and number of events N expected from Eq. 3.1 corresponding to an integrated luminosity of $\mathscr{L} = 2 fb^{-1}$, for different values of the momentum transfer squared $q^2 = s$ and of the antiproton momentum, p.

Table 2 shows the results of calculations for different values of the momentum transfer squared $q^2 = s$ and of the antiproton momentum, p.

The form factors were extracted from the angular distribution of electrons from e^+e^- pairs as a function of $\cos(\theta_{CM})$. Fig. 2 shows an example of such a distribution at $q^2 = 8.21$ $(GeV/c)^2$ with the generated, reconstructed, and efficiency corrected events drawn. The efficiency corrected events were fitted using Eq. 3.1 with G_E and G_M as a free fit parameters. The reconstruction efficiency coefficients were determined from an independent simulation. Fit results for different values of q^2 are shown in Fig. 3.

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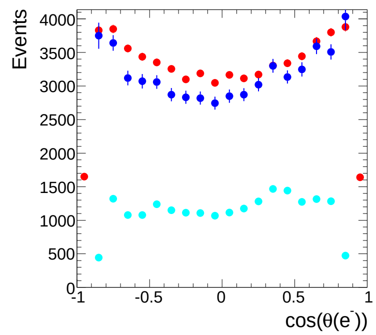

Figure 2: Angular distribution of electrons from e^+e^- pairs as a function of $\cos(\theta_{CM})$ at $q^2 = 8.21$ $(GeV/c)^2$ distribution in the CM frame of the generated (red dots), reconstructed (cyan dots), and efficiency corrected events (blue dots).

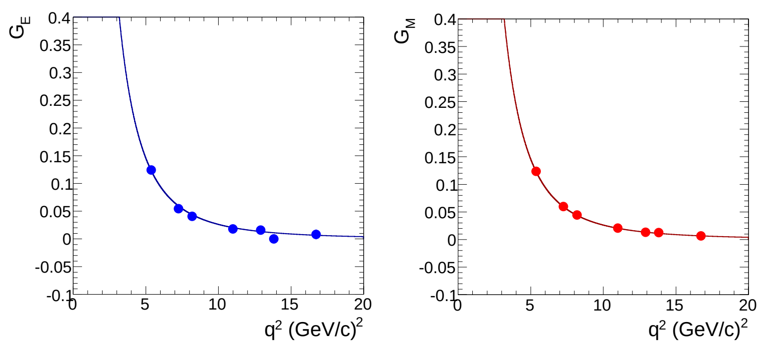

Figure 3: Extracted values of G_E and G_M (dots) plotted over their theoretically predicted values (lines).

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