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The ratio of $e^{\pm}p$ scattering cross sections predicted from the global fit of elastic ep data

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Abstract

We present predictions for the value of the cross section ratio $\sigma(e^+p \to e^+p)/\sigma(e^-p \to e^-p)$, determined from our fit of the elastic ep cross section and polarization data. In this fit we took into account the phenomenological two-photon exchange dispersive correction. The cross section ratios which are expected to be measured by the VEPP-3 experiment are computed. The kinematical region which will be covered by the E04-116 JLab experiment is also considered. It is shown that for both experiments the predicted cross section ratios deviate from unity within more than 3σ.

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1 Introduction

The electric and magnetic proton form factors can be obtained from the measurement of the elastic $ep \to ep$ cross section. The data are usually analyzed via the Rosenbluth separation technique. This amounts to write the reduced cross section, in the one-photon-exchange approximation, in units of the Mott cross section, as follows:

$$\sigma_{R,1\gamma}(Q^2,\epsilon) = G_{Mp}^2(Q^2) + \frac{\epsilon}{\tau}G_{Ep}^2(Q^2), \quad \tau = \frac{Q^2}{4M^2}, \ \ \epsilon^{-1} = 1 + 2(1+\tau)\tan^2(\theta/2)\,, \tag{1}$$

θ being the scattering angle, Q^2 the four momentum transfer, M the proton mass. For a given Q^2 value several measurements at different scattering angles are performed and then the magnetic $G_{Mp}(Q^2)$ and electric $G_{Ep}(Q^2)$ form factors can be simultaneously extracted (see, e.g. Ref. [1]).

Since the beginning of the 90's new longitudinally polarized electron beams became available. From that time, experiments on the elastic scattering of polarized electrons on unpolarized or polarized target started. In the experiments on the scattering of polarized electron on unpolarized proton target ($\vec{e}p \to e\vec{p}$) the transverse and longitudinal polarization of the recoil protons were measured. The ratio of these quantities is proportional (in Born approximation) to the form factors ratio $\mu_p G_{Ep}/G_{Mp}$. In the experiments on the scattering of polarized electrons on a polarized target ($\vec{e}\vec{p} \to ep$) the asymmetry was measured. This observable is also a function of the ratio of the electric and magnetic form factors.

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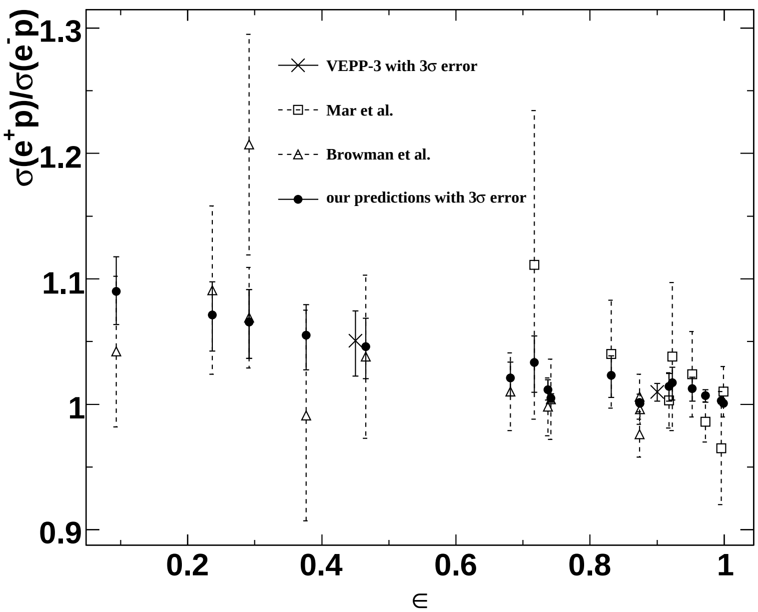

Figure 1: The ratio, Eq. (2). The open squares and triangles denote data points from Refs. [19] and [20] (the experimental error bars are denoted by dotted intervals). By black circles our predictions for [19] and [20] data are presented together with 3σ error bars (denoted by solid intervals). The crosses present our prediction for two points which are expected to be measured at the VEPP-3 experiment (together with 3σ error bars).

It turned out that the ratio $\mu_p G_{Ep}/G_{Mp}$ obtained from polarization measurements [2, 3, 4], for values of the four momentum transfer above 3 GeV^2, is in disagreement with the same quantity evaluated with the proton form factors extracted with the Rosenbluth separation technique.

An obvious remark is that the Rosenbluth separation method works less efficiently at large Q^2, the reason being that with increasing Q^2 the term $\epsilon G_{Ep}^2/\tau$ becomes significantly smaller than G_{Mp}^2 [see Eq.(1)]. Moreover it turns out that even a tiny additional correcting term to the reduced cross section (of the order of a few percent of the total σ_R) can significantly affect the extracted value of G_{Ep} and hence the form factor ratio $\mu_p G_{Ep}/G_{Mp}$. For most cross section data the "classical" radiative corrections have been applied [5]. This however could not solve the problem of the inconsistency between the form factor ratio obtained from Rosenbluth technique and polarization measurements.

The possibility to solve this problem by taking into account the contribution of the two-photon exchange corrections (TPE) was considered in different papers (see e.g. [6]). These corrections are natural candidate for solving the above outlined inconsistency. Indeed, at large Q^2 the contribution of TPE corrections to the reduced cross section is of the order of $\epsilon G_{Ep}^2/\tau$.

It has been shown that, by including TPE corrections in the data analysis, one can extract from the Rosenbluth separation proton electromagnetic form factors which are in agreement with the results of polarization measurements [6, 7, 8, 9]. It has been also shown that TPE corrections to the ratio of the transverse and longitudinal polarization of the recoil protons are smaller than experimental errors [6, 10] and can be, at present, neglected.

The above problem has been extensively studied by many authors from the phenomenological and theoretical point of view (for a recent review see, e.g. Ref. [11]). On the theoretical side the major difficulty is to take into account properly intermediate hadronic states, which contribute to the TPE amplitude [12]. However, the two-photon exchange contribution can be parameterized phenomenologically and the corresponding parameters can be determined from the experimental data [10, 13, 14, 15].

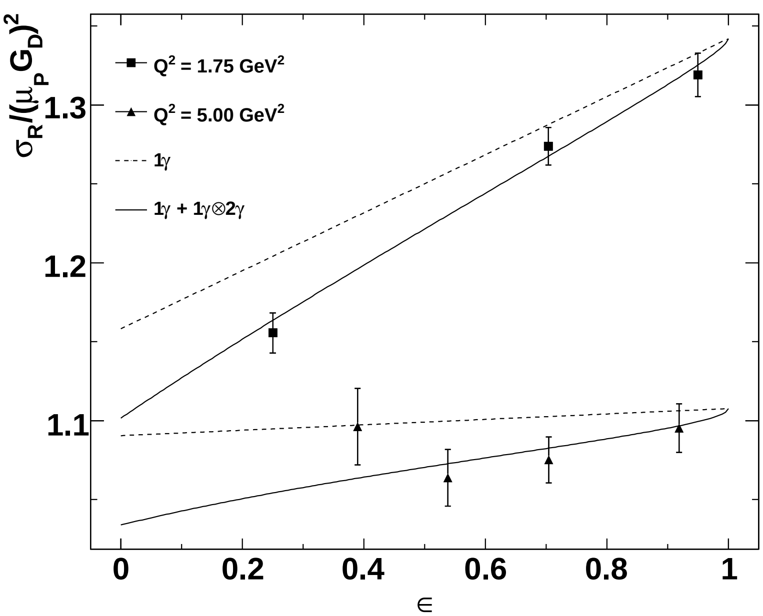

Figure 2: Plots of $\sigma_R/(\mu_p G_D)^2$ for $Q^2 = 1.75$ and 5.00 GeV^2. The data points are taken from Ref. [24]. The solid line denotes the reduced cross sections computed with the TPE dispersive term, given by Eq. (7). The dashed lines correspond to the same cross sections in Born approximation (i.e. without the TPE correction).

In the elastic electron-proton scattering process the leading TPE contribution is given by the interference between the Born and the TPE amplitudes. As a consequence the correcting term is proportional to the real (dispersive) part of the TPE amplitude and turns out to be odd in the charge of the projectile. Hence the TPE correction has opposite signs for electron-proton and positron-proton scattering. For this reason the measurement of the ratio

$$R_{e^+/e^-}(Q^2,\epsilon) \equiv \frac{\sigma(e^+p \to e^+p)}{\sigma(e^-p \to e^-p)} \tag{2}$$

provides a unique and model-independent possibility to determine the magnitude of the TPE correction.

Another possibility to measure the TPE effect is by observing the non-linearity in ϵ of the Rosenbluth data (see e. g. Fig. 2), which is implicated by the symmetry properties of the interaction [16]. However, up to now such nonlinearities are not visible [13, 17, 18]. Accurate measurements of new Rosenbluth data in a wide ϵ range are required to study this effect.

Measurements of the ratio (2) were performed in the 60's. In Fig. 1 some of the SLAC data [19, 20] for the ratio R_{e^+/e^-} are shown. One can see that the experimental uncertainties do not allow to draw any definite conclusion on the presence of TPE corrections, since the data are compatible with $R_{e^+/e^-} = 1$.

Two new experiments are under preparation, which will measure the elastic electron(positron)-proton scattering cross sections with higher accuracy. One of them will take place at the VEPP-3 storage ring [21], the approximate beam energy being around 1.6 GeV. Measurements at $\epsilon \approx 0.90$ and 0.45 with $Q^2 \approx 0.3$ and 1.5 GeV^2, respectively, are proposed. The second experiment was proposed at JLab [22]. Here a wide range of $\epsilon \in (0.1, 0.9)$ will be explored, with Q^2 in the range $(0.5, 3)$ GeV^2.

In this letter we give the expected value for the ratio R_{e^+/e^-}, in the kinematical range accessible to the above mentioned two new experiments. Our results are determined from the global fit of the *ep* elastic data [23]. We provide our predictions with the corresponding uncertainties, which are also obtained from our global fit.

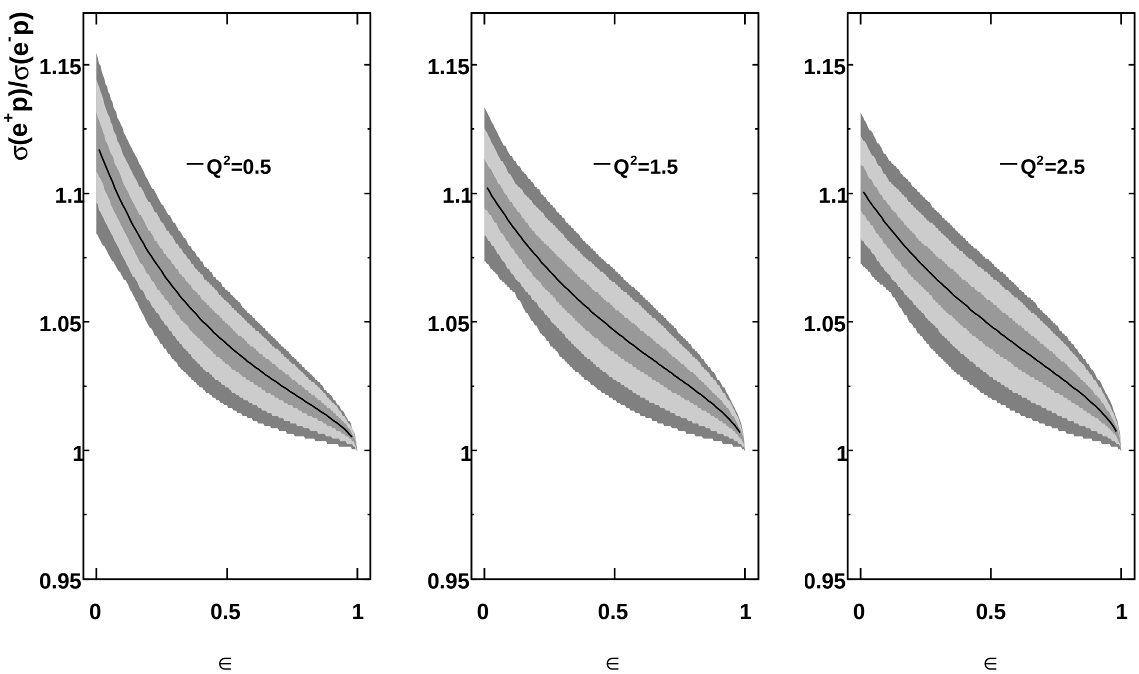

Figure 3: The ratio R_{e^+/e^-} computed for three values of Q^2 (0.5, 1.5 and 2.5 GeV^2) which will be explored in the JLab experiment E04-116. The shadowed regions denote 1σ (the most inner region), 2σ and 3σ (the most external region) calculated uncertainties.

2 Dispersive two-photon exchange contribution

In Ref. [23] we performed a global fit of the *ep* elastic cross section and polarization data. The cross section data were fitted by taking into account a TPE correcting term, which was added to the reduced cross section, according to Ref. [15], as follows:

$$\sigma_R(Q^2,\epsilon) \to \sigma_{R,1\gamma}(Q^2,\epsilon) + \delta_{1\gamma\otimes 2\gamma}(Q^2,\epsilon), \tag{3}$$

where $\delta_{1\gamma\otimes 2\gamma}$ is the TPE correction, due to one- and two-photon interference. On the other hand, as mentioned in the Introduction, the polarization data are practically not affected by TPE corrections. A decrease of the cross section due to a negative TPE correction allowed us to obtain form factors whose ratio is in agreement with the polarization data. Since the polarization data are necessary for the extraction of the TPE correction through the comparison with the cross section data, the global fit in Ref. [23] was limited to the kinematical range of the polarization data.

The dependence on ϵ of $\delta_{1\gamma\otimes 2\gamma}(Q^2,\epsilon)$ is constrained by the requirements of charge conjugation and crossing symmetry [16]. As a consequence, $\delta_{1\gamma\otimes 2\gamma}$ should satisfy the relation

$$\delta_{1\gamma\otimes 2\gamma}(Q^2,-y) = -\delta_{1\gamma\otimes 2\gamma}(Q^2,y), \tag{4}$$

where

$$y = \sqrt{\frac{1-\epsilon}{1+\epsilon}}. \tag{5}$$

Based on the above properties Chen *at al.* [15] proposed two parameterizations of the TPE term. In both of them the Q^2 dependence was given by the dipole form factor

$$G_D(Q^2) = \left(1 + \frac{Q^2}{0.71}\right)^{-2}, \tag{6}$$

which was multiplied by functions of y. Such a Q^2 dependence is heuristically justified by its simplicity and the effectiveness in the fit of the data (however, a different Q^2 dependence with double poles at $Q^2 = -1.5\,\mathrm{GeV}^2$ and $Q^2 = -0.71\,\mathrm{GeV}^2$ was proposed in Ref. [17]). In Ref. [23] we employed the form

$$\delta_{1\gamma\otimes 2\gamma}(Q^2, y) = G_D^2(Q^2)\left(\alpha y + \beta y^3\right), \tag{7}$$

which is one of the functional forms proposed in Ref. [15]. The best fit values obtained in Ref. [23] for the parameters α and β are[1]

$$\alpha = -0.36 \pm 0.09, \quad \beta = -0.08 \pm 0.09, \tag{8}$$

with 1σ uncertainties given by the square-roots of the diagonal elements of the covariance matrix[2]. In the following the uncertainties are evaluated using the correlated systematic uncertainties of the parameters obtained in Ref. [23] through a standard least-squares analysis of the data.

In Fig. 2 we plot the reduced cross sections (divided by $\mu_p^2 G_D^2$), computed for two Q^2 values, 1.75 and 5 GeV^2: the solid lines correspond to our global fit [23], including the TPE term. We recall that the goodness of fit (GoF) was GoF = 71%. By comparing the lines with and without TPE correction, one can see that the estimated TPE correction is small (of the order of a few percent), the major effect appearing at small ϵ values (which correspond to the largest y values).

We now discuss our prediction for the ratio R_{e^+/e^-}, which was already shown in Fig. 1 together with the old SLAC data. In this figure, for each point we computed the ratio (2) using the proton form factors and TPE correction term from our global data fit. The predicted points are plotted with the 3σ uncertainty. Although our prediction for the ratio is well above one at small epsilon, the SLAC data do not have sufficient accuracy to reveal a significant deviation from unity.

In the same figure we display also the two points which are going to be measured in the VEPP-3 experiment [21]. For the kinematical conditions of this experiment we obtained

$$R_{e^+/e^-}(Q^2 = 0.3\,\mathrm{GeV}^2, \epsilon = 0.90) = 1.010^{+0.003,+0.006,+0.007}_{-0.002,-0.005,-0.007},$$
$$R_{e^+/e^-}(Q^2 = 1.5\ \mathrm{GeV}^2, \epsilon = 0.45) = 1.051^{+0.009,+0.019,+0.024}_{-0.009,-0.019,-0.028},$$

where the 1σ, 2σ and 3σ errors are indicated. The predicted ratios are clearly above one, by more than 3σ.

Our predictions for the ratio R_{e^+/e^-} for the kinematical conditions of the E04-116 JLab experiment [22] are presented in Fig. 3. We plot R_{e^+/e^-} for three Q^2 values: 0.5, 1.5 and 2.5 GeV^2. The 1σ, 2σ and 3σ uncertainties are denoted by shadowed areas. In all the considered cases the predictions are above one even by more than 3σ.

In both experiments the foreseen accuracy of measurements will be sufficient to reveal the predicted deviation from unity of R_{e^+/e^-}. For the VEPP-3 experiment the systematic uncertainty is estimated to be below 0.3%, while for the JLab project it is predicted to be smaller than 1.0%. The statistical errors for the first experiment are expected to be around 1%, while for the second project the statistical uncertainties are foreseen to be smaller than $1 \div 2\%$ (see Fig. 34 of Ref. [22]).

In Fig. 4 we compare our predictions for R_{e^+/e^-} with those computed with pQCD in Ref. [25]. Since our fit of elastic *ep* data is valid for $Q^2 < 6$ GeV^2, we consider only the curves in Fig. 4 of Ref. [25] corresponding to $Q^2 = 2$ and 5 GeV^2. Our predictions for R_{e^+/e^-} are systematically lower than those in Ref. [25], but there is an agreement at the 2σ level.

[1] More precisely these values refer to fit II, but do not significantly differ from the ones of fit I of the above quoted reference.

[2] The covariance matrix and the table of χ^2 values in the parameter space are given in `http://www.nu.to.infn.it/pap/08/ff/ff.php`.

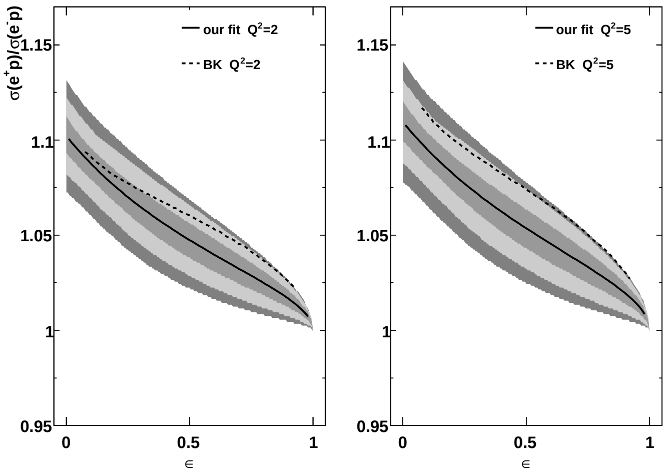

Figure 4: The ratio R_{e^+/e^-} computed for $Q^2 = 2$ and 5 GeV^2, compared with the corresponding predictions in Ref. [25]. The shadowed regions denote 1σ (the most inner region), 2σ and 3σ (the most external region) calculated uncertainties.

3 Conclusions

As it is well known, the ratio of the electric and magnetic form factors of the proton obtained from the measurement of the polarization of the recoil proton in the scattering of polarized electrons on unpolarized protons and that obtained from the measurement of the cross section in the elastic e^-p-scattering are not compatible with each other. It was suggested in several papers [6, 7, 8, 9] that this discrepancy can be resolved if one includes two-photon-exchange corrections.

If the hypothesis of the importance of the two-photon exchange term is correct, then, due to the interference of the one-photon and two-photon amplitudes, the cross sections in e^-p and e^+p elastic scattering are different.

These cross sections were measured in the past at SLAC [24], however the large errors in this experiment did not allow to draw definite conclusions about the TPE term. Two new high-precision experiments on the measurement of the ratio R_{e^+/e^-} of the cross sections of $e^\pm p$ elastic scattering are now at preparation at the VEPP-3 storage ring [21] and at JLab [22].

Having in mind these experiments, in this letter we performed the calculation of the ratio R_{e^+/e^-} in the ranges of Q^2 and ϵ which will be covered by these future measurements. We used the electromagnetic form factors of the proton and the parameters of the TPE term which were obtained from our global fit [23] of the data on the measurement of the cross section and polarization effects in elastic e^-p scattering. We have shown that the ratio R_{e^+/e^-} is significantly different from unity even if we take into account the 3σ uncertainty, which we obtained from the fit.

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