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Experimental search for two-hard-photon exchange in elastic *ep* experiments

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A remarkable change of paradigm was precipitated by the results, obtained in the last 12 years, of new measurements of the proton form factor ratio; the two form factors, G_{Ep} and G_{Mp}, are not in a constant ratio, as had been concluded from previous cross section experiments, and would be the case if charge and magnetization spatial distributions were the same. Rather, as the series of polarization measurements at JLab shows, the ratio $\mu_p G_{Ep}/G_{Mp}$ decreases smoothly from 1 at Q^2=0, to about 0.15 at Q^2=8.5 GeV^2, with Q^2 the negative of the four-momentum transfer squared. The interesting question is then: how can the results using two methods both related through the Born approximation, be found to lead to a different form factor ratio? The short answer is that cross sections require large radiative corrections, which tend to mask G_{Ep} for increasing Q^2, whereas recoil polarization experiments measure the ratio of two components of the recoil polarization, which tends to cancel the effect of radiative corrections. Radiative corrections to the cross section of *ep* scattering have a long history. They may just not be accurate enough when the ratio $G_{Ep}/G_{Mp} \approx 0.05$ and $\tau = Q^2/4m_p{}^2 \approx 2.5$, as is the case for the largest Q^2 for which we have double-polarization data, 8.5 GeV^2. For this Q^2 and with the Born cross section given by $d\sigma \approx G_{Ep}^2 + (\tau/\varepsilon)G_{Mp}^2$, with ε the kinematic factor, the contribution to the cross section of G_{Ep} becomes smaller than 0.1%, i.e. non-measurable in cross section experiments. The other hypothesis, is that the radiative corrections are incomplete, and that the exchange of two hard photons is the source of the discrepancy; the idea has been pursued in numerous works, but to this day there is no direct, experimental evidence that two-hard-photons exchange is the major source of the discrepancy.

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How we "visualize" the proton has changed remarkably in the last 12 years. A trigger to this change of "worldview" of the proton's structure has been a series of experiments at Jefferson Lab (Jlab), which established that the ratio of the elastic form factors, G_{Ep} and G_{Mp}, was not constant, but decreased systematically with the invariant mass squared, Q^2, of the virtual photon in *ep* scattering. Why the different results? The JLab experiments used the double-polarization technique in ${}^1H(\vec{e}p,e'\vec{p})$. Older experiments used the longitudinal-transverse (LT, or Rosenbluth h) separation method.

Cross sections are subject to large radiative corrections; these may not be accurate enough, or incomplete; it has become evident that the contribution to the elastic *ep* amplitude from the exchange of two hard photon, had been left out from the analysis of most earlier cross section experiments. The radiative corrections are weak when the ratio G_{Ep}/G_{Mp} is measured directly, as in double polarization experiments. This is in contrast to cross section measurements, where G_{Ep}^2 and G_{Mp}^2 are obtained by LT separation.

Here I will discuss aspects of elastic *ep* scattering, emphasizing the need to determine experimentally the role of higher order radiative corrections, and "what we know" we need to know.

The results of the first measurement of the proton's G_{Ep}/G_{Mp} ratio for Q^2>0.5 GeV^2 in a double-polarization experiment at Jefferson Lab (then known as CEBAF) in 1998, were published in 2000 [1]. The data for $\mu_p G_{Ep}/G_{Mp}$, where μ_p is the proton magnetic moment, shown in Fig. 1, seemed to disagree with the LT-separation (or Rosenbluth) cross section data available at the time [2, 3], which are shown in the lower panel of Fig. 1 only, as Q^2F_2/F_1, a ratio which can be obtained directly from the measured ratio $r = G_E/G_M$ as $\frac{F_2}{F_1} = \frac{(1-r)}{(\tau+r)}$, where $\tau = Q^2/4M^2$ and M^2 is the proton mass squared.

The data of GEp(I) have been reanalyzed since [4], and since 2010 we have the results of GEp(II) [5] and GEp(III) [6], as well as the reanalyzed data of GEp(II) [7], all shown in Fig. 2.

The firsts to suggest that the difference between cross section and double polarization results may be due to the hitherto neglected two-hard-photon exchange were Guichon and Vanderhaeghen [8], and Blunden et al. [9], in the same issue of Phys. Rev. Lett. In general, cross section data require large radiative corrections; double-polarization data for the ratio G_{Ep}/G_{Mp} do not: the radiative corrections affect the L and T terms similarly; the residual correction for double polarization is at the < 1-2% level. A number of calculations of the two-hard-photon contribution have been published since 2003. A partial list of calculations of the contribution of the two-hard-photon process to the cross section includes [10, 11, 12, 13, 14, 15].

A more recent Rosenbluth separation in Hall A agrees with the older data [16]. Overlap points in G_{Ep}/G_{Mp} show that polarization results are independent of the spectrometer used to rotate the longitudinal polarization component into a transverse one. The drastic difference between the results of the two kinds of experiments, illustrated in Fig.2, has thus been verified experimentally, and is irreducible. More information can be found in the review paper [17].

The ratio of G_{Ep} to the dipole form factor G_D is shown in Fig.3; one interpretation of this figure is that the uncertainty on G_{Ep} “explodes” near 3 GeV^2; as shown in Fig. 4, the relative contribution of G_{Ep} to the cross section becomes smaller than 10%, which is also the typical uncertainty on the data points, near values of $Q^2 \sim$ 3 GeV^2; near this Q^2 the relative contribution of G_{Ep} to the cross section becomes of order of the experimental uncertainty (10-20%) by $Q^2 \sim$ 3.5 GeV^2. This

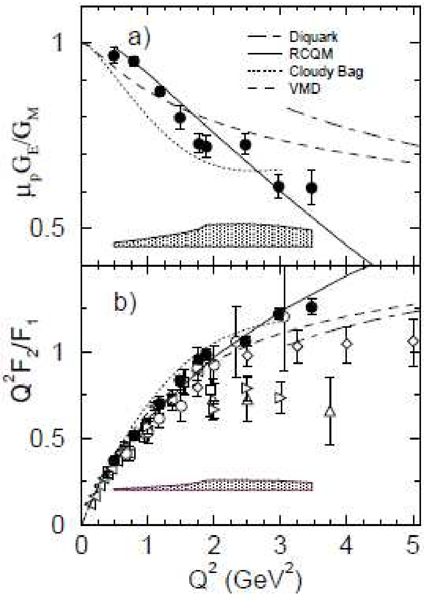

Figure 1: Results of the 1998 JLab GEp(I) experiments [1], suggesting different behavior for form factor ratio, than obtained in [2, 3].

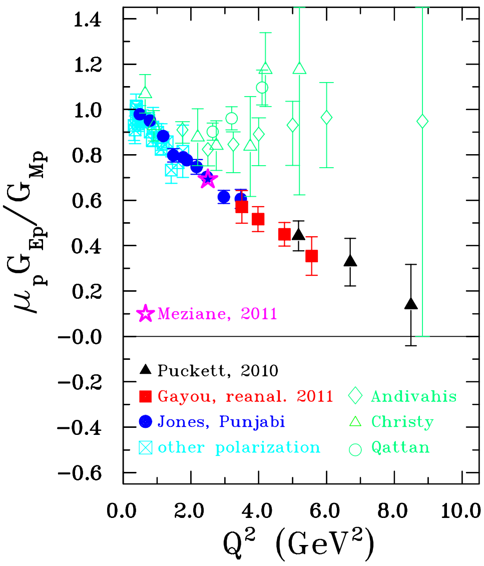

Figure 2: The complete set of JLab GEp experiments [4, 5, 6, 7], compared with the Rosenbluth data of Refs. [2, 3, 16].

behavior supports the suggestions that the "signal" for G_{Ep} simply disappears in the uncertainty of the data. Coincidence?

Fig 5. shows Rosenbluth plots for 3 selected Q^2 points from Andivahis *et al* [3]. The data before radiative correction are at the bottom, the same data after correction at the top of the figure; at a Q^2 of 5 GeV^2, the slope changes from negative to positive. Furthermore there is considerable uncertainty in radiative corrections, as illustrated in Fig. 6; here only the Q^2=5 GeV^2 data are displayed, with the original radiative correction, and those of refs. [13, 14]. For comparison, the slope deduced from the double-polarization results [5] is also shown. The discrepancy is of the order of the scatter of these 3 radiative corrections.The slope correction caused by radiative effect is systematically too large, resulting in anomalously large values of G_{Ep}^2.

Incompleteness of the radiative corrections is commonly thought to be at the origin of the discrepancy. The remaining problem is to demonstrate, on the basis of data, that earlier radiative corrections were incomplete because they did not include the contribution due to two-hard-photon exchange. See the most recent discussion of the two-photon exchange contribution in the review paper of Arrington et al. [18].

The most direct way to characterize a two-hard-photon contribution to the elastic *ep* cross section is to compare e^+p and e^-p scattering. There are no modern electron-positron data at this time, but three attempts to determine the two-hard-gamma contribution from the the $d\sigma e^+/d\sigma e^-$ ratio of cross sections are ongoing; they are based on the relation $(d\sigma_e^+ - d\sigma_e^-)/(d\sigma_e^+ + d\sigma_e^-) = 1 - 2d\sigma_{2\gamma}/(d\sigma_e^+ + d\sigma_e^-)$, where $d\sigma_{2\gamma}$ is the cross section contribution from two-photon exchange.

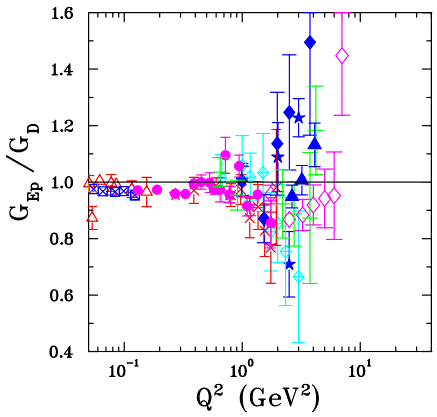

Figure 3: All Rosenbluth data for G_{Ep} divided by the dipole form factor, versus Q^2 [17]. Note that near 1-3 GeV^2, the information appears to vanish.

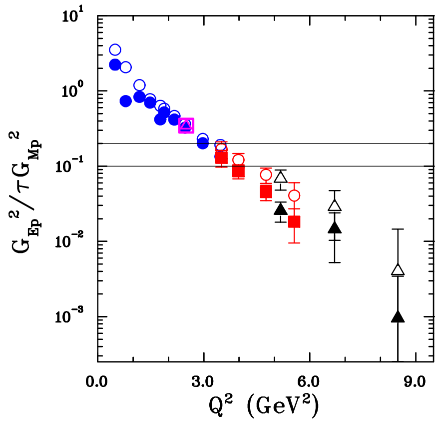

Figure 4: Relative contribution of G_{Ep} to the cross section, versus Q^2. Region between 2 horizontal lines is where experimental uncertainty becomes equal to relative G_{Ep} contribution.

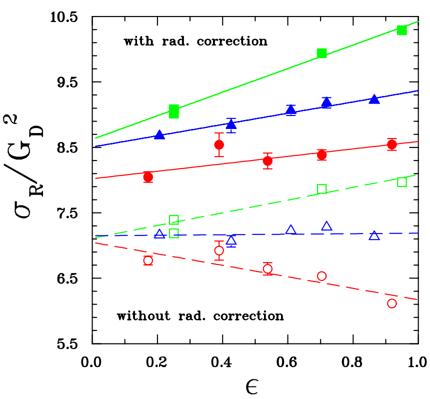

Figure 5: Rosenbluth plot for the Andivahis data[3]: dashed line before, solid line after radiative correction: red, blue and green for Q^2= 5, 3.25 and 1.75 GeV^2; illustrating need for precise radiative corrections as Q^2 increases.

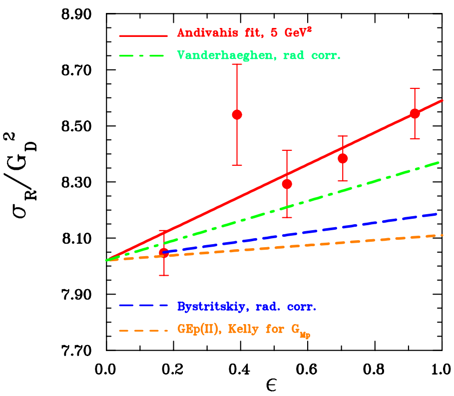

Figure 6: Rosenbluth plot for the Q^2 = 5 GeV^2 data of Andivahis *et al*[3], with original radiative correction, those of [3], [14] and [13]; shown for comparison is the slope calculated from the double-polarization results.

There are preliminary results from run I at VEPP-3 in Novosibirsk [19]. The Q^2 value for this run is 2.0 GeV^2, and ε=0.48 and 0.95; run II will include Q^2=1.6 GeV^2 and values of $\varepsilon < 0.5$.

At JLab in Hall B the CLAS collaboration obtained two-photon exchange data for Q^2 between 0.5 and 3 GeV^2, with $0.15 < \varepsilon < 0.95$ [20], which currently is in the data analysis phase.

The Olympus experiment at DESY, currently in data taking mode, should obtain data for $0.6 < Q^2 < 2.2$ GeV^2, for one value of ε at each Q^2 ranging from 0.905 to 0.367 [21]. Note that the ultimate results of these 3 experiments will be affected by radiative corrections, which are not identical for e^+ and e^-.

In a different approach, the GEp(2γ) experiment in Hall C at JLab recently measured the ratio

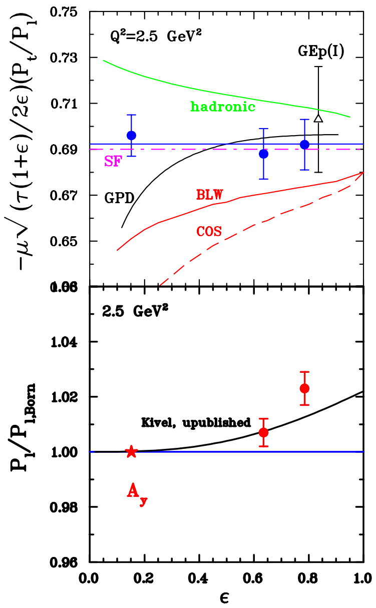

Figure 7: Results of the two-gamma experiment at JLab [22]. Top panel ratio which would be equal to $\mu_p G_{Ep}/G_{Mp}$ in the Born approximation. Bottom panel $P_\ell/P_{\ell,Born}$ for the 2 higher ε points; lowest ε point used to determine A_y.

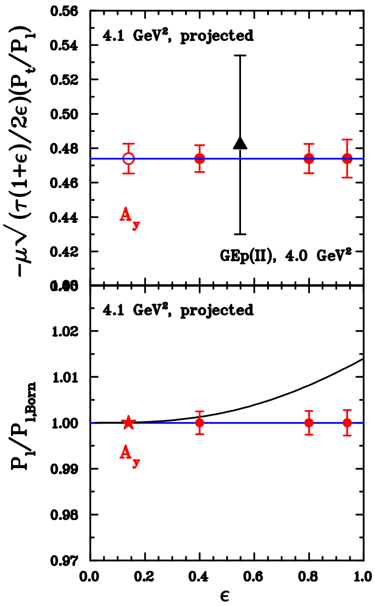

Figure 8: Possibility of a new measurement of P_t/P_ℓ and $P_\ell/P_{\ell,Born}$ at Jefferson Lab, after the energy upgrade to 12 GeV. In both figures 7 and 8 the line in the lower panel is from Kivel and Vanderhaeghen [23].

$-\sqrt{(1+\varepsilon)/2\varepsilon}P_t/P_\ell$, which strictly equals G_{Ep}/G_{Mp} in the one-photon (or Born) approximation, at a central value Q^2=2.49 GeV^2, and for three values of ε: 0.152, 0.635 and 0.785, with very small error bars [22]; P_t and P_ℓ are the transverse and longitudinal components of the polarization transferred to the proton. At the same time values of $P_\ell/P_{\ell,Born}$ where obtained at the two larger ε values, using the lowest ε data point to determine the analyzing power, A_z of the polarimeter for the common central proton momentum of 2.06 GeV/c. The results of these two measurements are shown in Fig. 7. The ratio $-\sqrt{(1+\varepsilon)/2\varepsilon}P_t/P_\ell$ appears constant, with value 0.6923 ± 0.0058 statistics, and very small systematic uncertainty. The ratio $P_\ell/P_{\ell,Born}$, displayed at the bottom of Fig. 7, shows a systematic deviation from 1 at the larger ε value, of up to 4.5 standard deviations. Such a behavior can be explained (see curve in lower panel of Fig. 7) with recent work by Kivel and Vanderhaeghen [23], which shows that the correction to the 3 form factors required in the presence of the interference of the one- and two-photon terms, do not cancel each other as $\varepsilon \to 1$.

Fig. 8 shows anticipated results of a possible experiment which will become feasible with the upgraded JLab accelerator. The choice of Q^2 of 4.1 is motivated by the availability of cross section and G_{Ep}/G_{Mp} data at similar values of Q^2, and the possibility to obtain statistical uncertainties of order 0.01 for all points. The total beam time required for such a measurement is 40 days.

To conclude, there is a clear need to understand the origin of the disagreement between cross section and double polarization data. Higher order graphs like two-hard-photon exchange are of intrinsic interest. Standard radiative corrections may need one more revision. Other experiments measuring *ep*, including parity violation searches and nuclear structure investigations, require upgraded radiative correction procedures. Whether double-polarization data truly determine invariant Born Form Factors F_{1p} and F_{2p}, after correction for radiative effects (including two-photon exchange) requires an urgent response; the answer has to come from data. The 2007-8 Hall C Jlab 2γ [22] test was at relatively low Q^2. It should be repeated at as large a Q^2 as possible. Such a test will become feasible with reasonable accuracy at Jlab, at Q^2=4.1 GeV^2, once the 11 GeV beam becomes available.

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