Charge-averaged elastic lepton-proton scattering cross section results from OLYMPUS

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Measurements of the proton's form factor ratio made with polarization transfer show a striking discrepancy relative to the ratio extracted from unpolarized elastic electron-proton scattering cross sections. One hypothesis is that the discrepancy is caused by hard two-photon exchange (TPE), a typically neglected radiative correction that may bias the two approaches differently. This hypothesis has been challenging to confirm. Theoretical estimates of TPE are model-dependent, and recent experimental determinations of TPE lacked the kinematic reach to be conclusive. The possible impact of TPE remains a cloud over our knowledge of the proton's form factors. Recently, the OLYMPUS experiment published new elastic scattering cross sections that are insensitive to the effects of TPE: specifically the average of electron-proton and positron-proton cross sections. The OLYMPUS experiment, conducted at DESY, Hamburg, measured elastic $e^- p$ and $e^+ p$ scattering by detecting the scattered lepton and recoiling proton in coincidence in a large-acceptance, toroidal magnetic spectrometer. OLYMPUS was designed to measure the $e^+ p / e^- p$ cross section ratio to isolate the effects of TPE. By exploiting the over determined kinematics of the reaction, the absolute efficiency of spectrometer could be verified, allowing cross sections to be extracted from the data. These results can help refine our knowledge of the proton's form factors, especially in the squared momentum-transfer region of 1–2 GeV^2, where some previous measurements are in tension.

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1. Introduction

The proton's electromagnetic form factors, G_E and G_M, show a significant discrepancy depending on the technique used to measure them. When determined from unpolarized elastic electron scattering cross sections, the form factors generally exhibit scaling, i.e., the ratio $\mu_p G_E/G_M$ is approximately constant as a function of momentum transfer, Q^2. By contrast, measurements of polarization transfer or other equivalent polarization observables indicate a sharply decreasing ratio, as shown in Fig. 1 left. The leading hypothesis is that the effects of hard two-photon exchange (TPE), a typically neglected radiative correction, might be affecting the two techniques differently [1, 2]. Several recent experiments have attempted to measure hard TPE directly by comparing positron-proton and electron-proton elastic scattering cross sections, but the results have not been conclusive [3–5]. Accounting for hard TPE remains a problem for understanding the proton form factors at high Q^2. For a recent review, see Ref. [6].
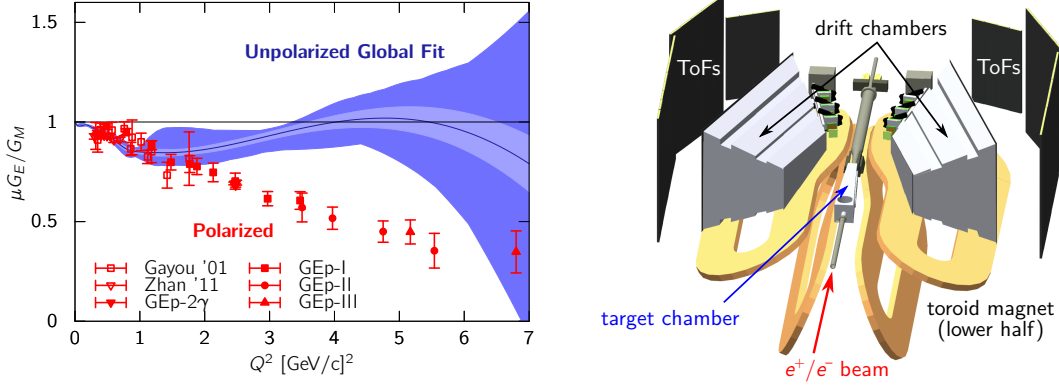
Figure 1: Left: the protons form factor ratio, $\mu_p G_E/G_M$, shows a striking discrepancy between unpolarized Rosenbluth separations and direct measurements using polarization observables. The unpolarized global fit comes from Ref. [7]. The polarized data are from Refs. [8–12]. Right: illustration of the OLYMPUS detector, described in detail in Ref. [13].

One of these recent experiments, OLYMPUS, has recently published absolute cross sections for both electron and positron elastic scattering [14]. The average of the two—the lepton charge averaged cross section—has the convenient feature of being insensitive to two-photon exchange effects at lowest order. This observable can help constrain proton form factors by removing the uncertainty associated with two photon exchange corrections.

2. The OLYMPUS Experiment

The OLYMPUS Experiment collected data at DESY, in Hamburg, Germany in 2012. Alternating beams of electrons and positrons in the DORIS storage ring were passed through a windowless unpolarized hydrogen target that was internal to the ring vacuum [15]. The OLYMPUS spectrometer [13] consisted of two instrumented sectors of an 8-coil toroid magnet [16] surrounding the target, shown in Fig. 1 right. Drift chambers were used for charged particle tracking and panels time-of-flight (ToF) scintillators were used for triggering, timing, and particle identification. Scattered leptons and recoiling protons were detected in coincidence and over-determined kinematics were used to cleanly separate elastic scattering events from inelastic background. The relative luminosity

between electron and positron running modes was determined from the rate of multi-interaction events in a pair of lead fluoride calorimeters positioned downstream at the angle of symmetric Møller/Bhabha scattering [17].

OLYMPUS's primary result was a measurement of the ratio of positron-proton to electron-proton elastic scattering cross sections, i.e., $R_{2\gamma} \equiv \sigma_{e^+p}/\sigma_{e^-p}$, shown in Fig. 2 left [5]. The results show a definitive indication of TPE: $R_{2\gamma}$ has a positive slope with increasing Q^2 (and decreasing ϵ). However the results are generally below theoretical predictions [7, 18]. It is not clear whether this slight disagreement is due to additional effects not accounted for in the predictions or to the overall normalization of the experiment (estimated to be better than ±0.5%). In any case, the OLYMPUS results are completely consistent with the magnitude of the form factor discrepancy in the Q^2 range covered by the experiment [19].

3. Charge-Averaged Cross Section Analysis

While the ratio $\sigma_{e^+p}/\sigma_{e^-p}$ amplifies the effects of TPE, the lepton charge-averaged cross section, $(\sigma_{e^+p} + \sigma_{e^-p})/2$, cancels the effects of TPE at lowest order. This combination therefore provides a more accurate measure of the Born cross section, removing the need to apply a correction for hard TPE.

Determining absolute cross sections was difficult for OLYMPUS, which was designed to measure cross section ratios in which the effects of acceptance, efficiency, and absolute luminosity normalization largely cancel. Nevertheless, the over-determined kinematics in elastic scattering allowed several cross checks to be performed in order to quantify the uncertainty coming from each effect. The efficiency of each sub-detector element—each scintillator panel and each drift chamber cell—was determined from data and then modelled in a Geant4 simulation. The efficiency for reconstructing elastic scattering events was determined from simulation. To cross check that there was no additional tracking inefficiency in real data relative to simulated data, elastic events were identified using the lepton (or proton) track information alone, to determine the probability for the successful reconstruction of the opposite side proton (or lepton). There was no indication of any additional tracking inefficiency, at the percent level.
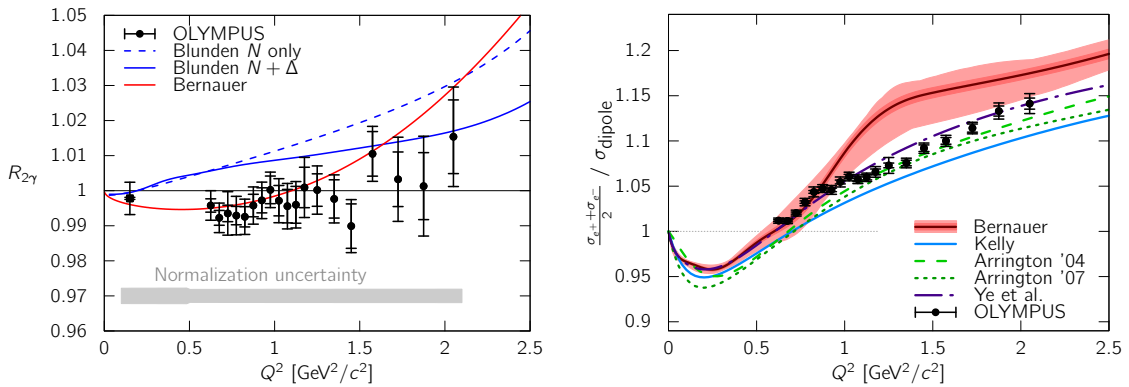
Figure 2: Left: the OLYMPUS measurement of $R_{2\gamma}$ [5] showed a slight increase with Q^2 as expected from the two-photon exchange hypothesis, but was slightly lower than theoretical expectations [7, 18]. Right: The results for the charge-averaged cross section compared to recent proton form-factor predictions [20–23]. A normalization uncertainty of ±7.5% is not shown.

OLYMPUS had no mechanism to determine the absolute luminosity, which is a combination of the well-measured beam current and the crudely known density of the hydrogen gas target. The best measure of the absolute luminosity came from the forward Møller/Bhabha calorimeters, but even this was estimated to have an accuracy of ±7%. The OLYMPUS results, therefore, are primarily a measure of the shape of the cross section, rather than one of absolute scale.

4. Results

The results [14] are shown in Fig. 2 right, in comparison to recent global fits of proton cross section data [20–23]. The results are in good qualitative agreement with these global fits. However, the data do not show the cusp predicted by the Bernauer et al. fit [7]. It will be interesting to see how this cusp changes when the Bernauer fit is updated to include the new OLYMPUS data. In general, the OLYMPUS results can help constrain future global fits with reduced ambiguity from uncertain corrections for hard TPE.

5. Summary

Data from the OLYMPUS Experiment were analyzed to extract absolute cross sections for both electron-proton and positron-proton elastic scattering. The average of the two is unaffected by hard TPE, giving robust access to the Born cross section and the proton's electromagnetic form factors. These results will aid future global fits to constrain G_E and G_M in the squared momentum transfer range of $0.6 < Q^2 < 2.0$ GeV$^2/c^2$.

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