Hard Two-photon Contribution to Elastic Lepton-Proton Scattering Determined by the OLYMPUS Experiment

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The OLYMPUS collaboration reports on a precision measurement of the positron-proton to electron-proton elastic cross section ratio, $R_{2\gamma}$, a direct measure of the contribution of hard two-photon exchange to the elastic cross section. In the OLYMPUS measurement, 2.01 GeV electron and positron beams were directed through a hydrogen gas target internal to the DORIS storage ring at DESY. A toroidal magnetic spectrometer instrumented with drift chambers and time-of-flight scintillators detected elastically scattered leptons in coincidence with recoiling protons over a scattering angle range of $\approx 20^\circ$ to 80°. The relative luminosity between the two beam species was monitored using tracking telescopes of interleaved GEM and MWPC detectors at 12°, as well as symmetric Møller/Bhabha calorimeters at 1.29°. A total integrated luminosity of 4.5 fb^{-1} was collected. In the extraction of $R_{2\gamma}$, radiative effects were taken into account using a Monte Carlo generator to simulate the convolutions of internal bremsstrahlung with experiment-specific conditions such as detector acceptance and reconstruction efficiency. The resulting values of $R_{2\gamma}$, presented here for $0.456 < \epsilon < 0.978$, are smaller than hadronic TPE calculations predict, but are consistent with phenomenological models.

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Measurements of the proton's elastic form factor ratio, $\mu_p G_E^p/G_M^p$, using polarization techniques show a dramatic discrepancy with the ratio obtained using the traditional Rosenbluth technique in unpolarized cross section measurements [1, 2]. One hypothesis for the cause of this discrepancy is a contribution to the cross section from hard two-photon exchange (TPE), which is not included in standard radiative corrections and would affect the two measurement techniques differently [3, 4]. Standard radiative correction prescriptions account for two-photon exchange only in the soft limit, in which one photon carries negligible momentum [5, 6]. There is no model-independent formalism for calculating hard TPE. Some model dependent calculations suggest that TPE is responsible for the form factor discrepancy [7–10] while others contradict that finding [11].

Hard TPE can be quantified from a measurement of $R_{2\gamma}$, the ratio of positron-proton to electron-proton elastic cross sections that have been corrected for the standard set of radiative effects, including soft TPE. The interference of one- and two-photon exchange is odd in the sign of the lepton charge, so any deviation in $R_{2\gamma}$ from unity can be attributed to hard TPE. The OLYMPUS experiment [12], as well as two recent experiments at VEPP-3 [13] and JLab [14], have measured $R_{2\gamma}$ to specifically determine if hard TPE is sufficient to explain the observed discrepancy in the protons form factors, or if some additional explanation is needed.

Both the magnitude of $R_{2\gamma}$ and its kinematic dependence are relevant. If hard TPE is the cause of the discrepancy, phenomenological models [15–18] predict $R_{2\gamma}$ should rise with decreasing ϵ and increasing Q^2. Here, ϵ is the virtual photon polarization parameter given by $[1 + 2(1 + \tau)\tan^2(\theta_e/2)]^{-1}$ where θ_e is the lepton scattering angle and $\tau = Q^2/(4M_p^2)$ where M_p is the proton mass, and $-Q^2 \equiv q_\mu q^\mu$ is the four-momentum transfer squared.

Only a brief overview of the OLYMPUS experiment is given here (see [12] for a detailed description). The OLYMPUS experiment took data in the last running of the DORIS electron/positron storage ring at DESY, Hamburg, Germany. The DORIS power supplies were modified to allow a daily reversal of the lepton sign. The experiment collected a total integrated luminosity of 4.5 fb^{-1}. The 2.01 GeV stored beams with up to 65 mA of current passed through a windowless, unpolarized hydrogen gas target with an areal density of approximately 3×10^{15} atoms/cm^2 [19].

The detector was based on the former MIT-Bates BLAST detector [20]: a toroidal magnetic spectrometer with the two horizontal sections instrumented with large acceptance ($20^\circ < \theta < 80^\circ$, $-15^\circ < \phi < 15^\circ$) drift chambers (DCs) for 3D particle tracking and walls of time-of-flight scintillator bars (ToFs) for triggering and particle identification. To a good approximation, the detector system was left-right symmetric and this was used as a cross check in the analysis. Because of excessive rates in the DC with negative toroid polarity (low-energy electrons would be bent into the DCs) most of the data taking was carried out with positive polarity.

Two new detector systems were designed and built to monitor the luminosity. These were a symmetric Møller/Bhabha calorimeter (SYMB) at 1.29° [21] and two telescopes of three triple gas electron multiplier (GEM) detectors interleaved with three multi-wire proportional chambers (MWPCs) mounted at 12°.

The trigger system selected candidate events that resulted from a lepton and proton detected in coincidence in opposite sectors, and these were read out by the data acquisition system and stored to disk.

An optical survey of all detector positions was made and the magnetic field was mapped throughout the tracking volume [22].

A complete Monte Carlo (MC) simulation of the experiment was developed in order to account for the differences between electrons and positrons with respect to radiative effects, changing beam position and energy, the spectrometer acceptance, track reconstruction efficiency, and elastic event selection. Rather than correct for each effect individually, the simulation allowed the complete forward propagation of the correlations amongst all these effects. The ratio we report is given by:

$$R_{2\gamma} = \left[\frac{N_{\text{exp}}(e^+)}{N_{\text{exp}}(e^-)}\right] \Big/ \left[\frac{N_{\text{MC}}(e^+)}{N_{\text{MC}}(e^-)}\right]. \qquad (1)$$

where N_i are the observed and simulated counts.

The first stage in the simulation was a radiative event generator developed specifically for OLYMPUS [18, 23]. This generator produced lepton-proton events weighted by several different radiative cross section models. In this letter, the results from two models are presented; one accounting for radiative effects to order α^3 and the other accounting for radiative effects to all orders through exponentiation. The former approach is equivalent to the ESEPP generator [24] and is most comparable to the results from other recent TPE experiments. The effect of the latter approach is less than the former by as much as 1 % at low ϵ, indicating that higher-order effects in radiative corrections are significant.

Particle trajectories were simulated using a three-dimensional model of the apparatus and then digitized to produce simulated data in exactly the same format as the experimental data. This digitization procedure accounted for the efficiency and resolution of individual detector elements, determined using data-driven approaches. Both the experimental and simulated data were analyzed with the same analysis code.

Track reconstruction was performed by using a pattern matching procedure on detector signals to identify track candidates. Then two distinct algorithms were employed to fit the track initial conditions: momentum, scattering angles, and vertex position.

Four independent elastic event selection routines were developed [18, 23, 25, 26], and the results presented are the average of the four with the statistical uncertainty calculated as the average of the statistical uncertainty of each analysis. Two additional routines are in preparation [27, 28]. Each routine uses different approaches, but all leverage the fact that the kinematics of elastic events are over-determined so that cuts on reconstructed kinematic quantities—momenta, angles, time-of-flight, vertex positions of the lepton and proton—could be used to reduce background from the sample of elastic events. Time-of-flight was used effectively to discriminate leptons from protons. Cuts on the proton acceptance were used to avoid acceptance edge effects. All of the routines utilized a background subtraction procedure, and all confirmed that the background rates were similar for electron and positron modes. Background typically varied from negligible at low Q^2 to ≈ 20 % at high Q^2. The routines

TABLE I. Contributions to the systematic uncertainty in $R_{2\gamma}$.

Contribution	Uncertainty in $R_{2\gamma}$
Beam energy	0.04–0.13 %
MIE luminosity	0.36 %
Geometry	0.25 %
Tracking efficiency	0.20 %
Elastic selection and background subtraction	0.25–1.17 %

binned elastic events according to the reconstructed proton angle, as this reconstruction was identical in electron and positron modes. We report results on a subset of the total recorded data selected for optimal running conditions, corresponding to 3.1 fb^{-1} of integrated luminosity.

The integrated luminosity for each beam species was monitored using four independent methods, which all yielded consistent results. Measuring multi-interaction event rates was finally chosen to determine the luminosity for each beam species. This method compared the relative rates for lepton-lepton coincidences in the SYMB with the rates for detecting a $\sim$ 2 GeV lepton from lepton-proton elastic scattering in coincidence with the lepton-lepton coincidence [18, 29]. This method of using multi-interaction events (MIEs) produced a 0.36 % uncertainty in the relative luminosity.

Choosing the MIE method as normalisation allowed the redundant pair of tracking telescopes at 12° to measure elastic ep scattered leptons at 12° in coincidence with recoil protons in the DCs around 72° that measured $R_{2\gamma}$ at $\epsilon = 0.978$ with negligible statistical uncertainty [25].

Table I summarizes the dominant contributions to the systematic uncertainty in $R_{2\gamma}$. The uncertainty from geometry was estimated from the differences between $R_{2\gamma}$ extracted from left-lepton versus right-lepton events. The uncertainty from tracking efficiency was estimated from the performance of the two different tracking algorithms. The uncertainty from elastic selection was estimated from the variance in $R_{2\gamma}$ produced by the different selection routines.

We want to emphasize that radiative corrections have a large effect on the OLYMPUS determination of $R_{2\gamma}$. The corrections to $R_{2\gamma}$ are driven by the lepton charge-odd corrections: soft TPE and lepton-proton bremsstrahlung interference. In the OLYMPUS analysis, radiative effects cannot be unfolded from the effects of detector efficiency, acceptance, etc., but the magnitude of radiative effects on $R_{2\gamma}$ can be estimated by comparing the full simulation with one where the events are re-weighted with the first Born approximation weights. This ratio using four different models is shown in Fig. 1. We find that the corrections are approximately 5–6% at the lowest ϵ values, and, furthermore, that higher order effects can alter the correction by as much as 1%.

The OLYMPUS determination of $R_{2\gamma}$ as a function of

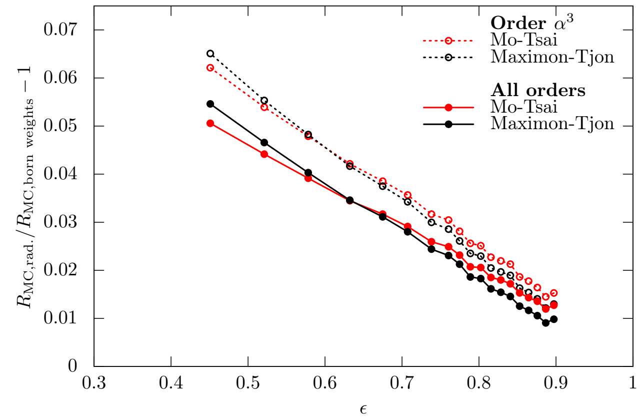

FIG. 1. Approximate effect of radiative corrections versus ϵ are on the order of several percent, depending on the model used, and whether the Mo-Tsai [5] or Maximon-Tjon [6] definition of soft TPE is used.

Bin	$\langle\epsilon\rangle$	$\langle Q^2\rangle$ (GeV/c)^2	$R_{2\gamma}$ (a)	$R_{2\gamma}$ (b)	$\delta_{\mathrm{stat.}}$	$\delta_{\mathrm{syst.}}$ uncorr.	$\delta_{\mathrm{syst.}}$ corr.
0	0.978	0.165	0.9971	0.9967	0.0003	0.0046	0.0036
1	0.898	0.624	0.9920	0.9948	0.0019	0.0037	0.0045
2	0.887	0.674	0.9888	0.9913	0.0021	0.0042	0.0045
3	0.876	0.724	0.9897	0.9927	0.0023	0.0060	0.0045
4	0.865	0.774	0.9883	0.9921	0.0026	0.0050	0.0045
5	0.853	0.824	0.9879	0.9918	0.0029	0.0039	0.0045
6	0.841	0.874	0.9907	0.9952	0.0032	0.0042	0.0045
7	0.829	0.924	0.9919	0.9967	0.0036	0.0033	0.0045
8	0.816	0.974	0.9950	0.9998	0.0039	0.0033	0.0045
9	0.803	1.024	0.9913	0.9969	0.0043	0.0040	0.0045
10	0.789	1.074	0.9905	0.9955	0.0047	0.0050	0.0045
11	0.775	1.124	0.9904	0.9960	0.0052	0.0041	0.0045
12	0.761	1.174	0.9950	1.0011	0.0057	0.0063	0.0045
13	0.739	1.246	0.9945	1.0007	0.0046	0.0056	0.0045
14	0.708	1.347	0.9915	0.9985	0.0054	0.0049	0.0046
15	0.676	1.447	0.9842	0.9912	0.0063	0.0050	0.0046
16	0.635	1.568	1.0043	1.0126	0.0063	0.0055	0.0046
17	0.581	1.718	0.9968	1.0063	0.0077	0.0096	0.0046
18	0.524	1.868	0.9953	1.0055	0.0095	0.0118	0.0046
19	0.456	2.038	1.0089	1.0212	0.0104	0.0108	0.0046

TABLE II. $R_{2\gamma}$ as determined using the Mo-Tsai [5] convention for soft two-photon exchange accounting for radiative effects to order α^3 (a), and to all orders (b).

ϵ and Q^2 is provided in Table II for two different radiative correction models. The results using the order-α^3 model are shown in Fig. 2, along with the theoretical calculation of Blunden [30], and two phenomenological predictions [17, 18] based on global fits to both unpolarized and polarized measurements of the proton form factors. OLYMPUS finds that the contribution from hard TPE is small at this beam energy, and that $R_{2\gamma}$ is consistent with or below unity over the entire range of ϵ, as well as below the theoretical prediction. However, the results are largely consistent with the phenomenological predictions. The phenomenological predictions suggest that the form

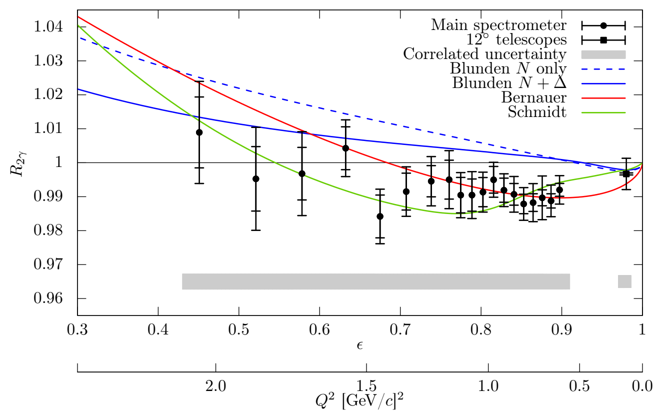

FIG. 2. $R_{2\gamma}$ with statistical and systematic (both correlated and uncorrelated) uncertainties from Table II for the order α^3 radiative corrections, using the Mo-Tsai [5] convention for soft two-photon exchange. Note the uncertainty of the 12° data point at $\epsilon = 0.978$ is completely dominated by the systematic uncertainty.

factor discrepancy is not large at the kinematics accessed by OLYMPUS. Furthermore the OLYMPUS results are consistent with the results from VEPP-3 and JLab. The TPE calculations which bring the form factor ratio measurements into agreement at large Q^2 predict a larger effect at the energies directly measured so far. Therefore, it is not evident, nor ruled out, that TPE is also driving the bulk of the difference at large Q^2. This needs to be tested in future measurement of TPE at larger Q^2.

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