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

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(Dated: October 31, 2016)

The OLYMPUS experiment here reports on a precision measurement of the ratio of positron-proton to electron-proton elastic cross sections, $R_{2\gamma}$, so named because it is a direct measure of the contribution of hard two-photon exchange (TPE) 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, Hamburg, Germany. 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 the internal bremsstrahlung with experiment-specific conditions such as detector acceptance and reconstruction efficiency. The resulting values of $R_{2\gamma}$, presented here over a range of ϵ from 0.978 to 0.456, are smaller than hadronic TPE calculations predict but are consistent with phenomenological predictions.

PACS numbers: 25.30.Bf 25.30.Hm 13.60.Fz 13.40.Gp 29.30.-h
Keywords: elastic electron scattering; elastic positron scattering; two-photon exchange; form-factor ratio

Measurements of the proton's 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 it 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 radiative effects including soft TPE. The interference of one- and two-photon exchange is odd in the sign of the lepton charge. After accounting for the standard set of radiative effects including soft TPE, any deviation in $R_{2\gamma}$ from unity can be attributed to hard TPE. The OLYMPUS experiment [12], as well as several recent experiments [13, 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 $R_{2\gamma}$ to rise as a function of decreasing $\epsilon \equiv [1 + 2(1+\tau)\tan^2(\theta_e/2)]^{-1}$, the virtual photon polarization parameter, where θ_e is the lepton scattering angle, $\tau = Q^2/(4M_p^2)$, M_p is the proton mass, and Q^2 is the four-momentum transfer squared. Furthermore, these models predict $R_{2\gamma}$ to tend to 1 as $\epsilon \to 1$, and to increase with larger Q^2.

Only a brief overview of the OLYMPUS experiment will be 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 [19] with an areal density of approximately 3×10^{15} atoms/cm^2.

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 ($20° < \theta < 80°$, $-15° < \phi < 15°$) drift chambers (DCs) for 3D particle tracking and walls of time-of-flight scintillator bars (ToFs) for triggering and for particle identification. To a good approximation, the detector system was left-right symmetric and this was used as a cross check in analysis. Because of excessive rates in the DC with negative toroid polarity (low-energy electrons would be bend into the DCs) most of the data taking was carried out with positive polarity.

Three 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 GEM detectors interleaved with three MWPC detectors 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.

A complete optical survey of the 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 between all of these effects. The ratio we report is given by

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

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 radiatively-corrected 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 latter approach is different from the former by as much as a percent at low-ϵ, indicating that uncertainties in radiative corrections from higher order effects are significant.

Particle trajectories were simulated using a three-dimensional computer model of the apparatus and then digitized to produce simulated data in the exact 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 software.

Track reconstruction was performed by first using a pattern matching approach on detector signals to first identify track candidates, and 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 in this letter reflect the average of the four (two additional selection routines are in preparation [27, 28]). The routines use different approaches but all leverage the fact that the kinematics of elastic events were over-constrained so that cuts on reconstructed kinematic quantities—momenta, angles, time-of-flight, vertex positions of the lepton and proton—could be used to remove background from the sample of elastic events. Timing 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. The routines binned elastic events according to

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%

the reconstructed proton angle, as this reconstruction was identical between 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 with four methods.

1) A simple slow control measurement using the beam current and the target density (determined from the gas flow and a detailed molecular flow simulation) provided a 5% absolute luminosity measurement and a 2% relative measure between beam species.

2) The symmetric Møller and Bhabha scattering rates in the SYMB provided a precise luminosity measurement. Unfortunately, the significant difference between the Møller and Bhabha cross sections, coupled with uncertainty in the beam and detector positions limited the accuracy to $\pm 3\%$ on the relative luminosity.

3) The problems with the SYMB could be circumvented by comparing the relative rates for lepton-lepton coincidences with that for detecting a ~ 2 GeV lepton from lepton-proton elastic scattering in coincidence with the lepton-lepton coincidence [29]. This method of using multi-interaction events (MIEs) produced a 0.36% uncertainty in the relative luminosity between beam species.

4) The 12° MWPC detectors tracked leptons elastically scattered in both the left and right sectors in coincidence with the recoil proton tracked in the DC and ToF around 76°. Combined with the MC simulation of ep elastic scattering, the 12° system had an uncertainty of 2.4% on an absolute luminosity determination and a better than 0.5% uncertainty on the relative luminosity determination, assuming that TPE effects are negligible at these kinematics.

We chose to use to the luminosity determination from the MIE method, which allowed the 12° system to deliver an additional $R_{2\gamma}$ data point.

Table I summarizes the 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.

Bin	$\langle\epsilon\rangle$	$\langle Q^2\rangle$ $(\mathrm{GeV}/c)^2$	$R_{2\gamma}$ (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).

The OLYMPUS determination of $R_{2\gamma}$ as a function of ϵ and Q^2 is provided in table II

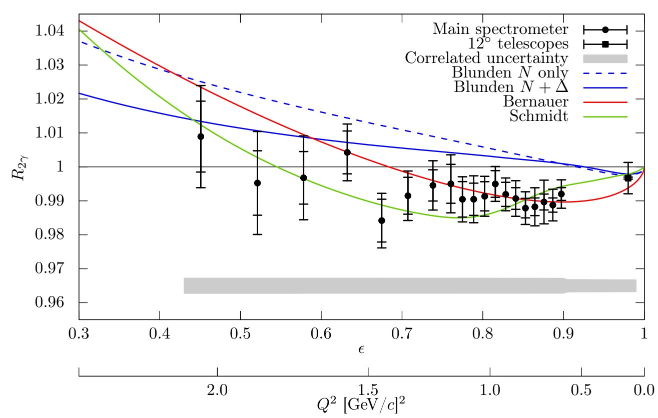

FIG. 1. $R_{2\gamma}$ with statistical and systematic (both correlated and uncorrelated) uncertainties from Table II for the order α^3 radiative corrections, using the Mo-Tsai convention for soft two-photon exchange.

for two different radiative correction models. The results using the order-α^3 model are shown in fig. 1, along with the theoretical calculation of Blunden et al. [30], and two phenomenological predictions [17, 18]. 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, below the theory prediction. However, the results are largely consistent with phenomenological predictions based on global fits to both unpolarized and polarized measurements of the proton form factors. The phenomenological predictions suggest that the form factor discrepancy is not large at the kinematics accessible by OLYMPUS. The TPE hypothesis remains viable, since $R_{2\gamma}$ may be large at different kinematics, namely for higher beam energy and larger Q^2.

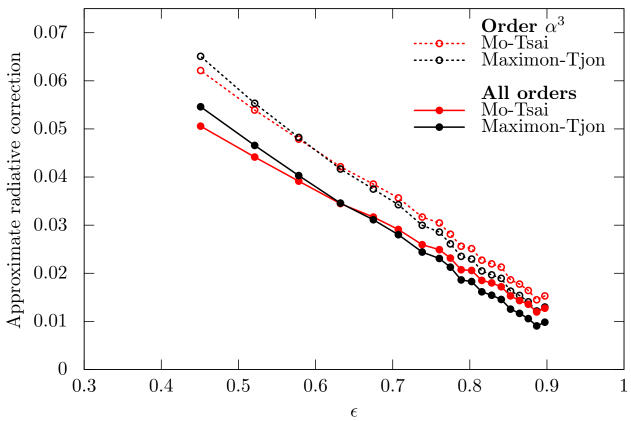

FIG. 2. The radiative corrections are on the order of several percent, depending on the model used, and whether the Mo-Tsai or Maximon-Tjon definition of soft TPE is used.

We 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 their magnitude can be estimated approximately by re-weighting simulated events. The approximate radiative corrections produced using four different models are shown in fig. 2. We find that the corrections are approximately 5–6% at the lowest ϵ data, and, furthermore, that higher order effects can alter the correction by as much as 1%.

This work was supported by numerous funding agencies which we gratefully acknowledge: the Ministry of Education and Science of Armenia, the Deutsche Forschungsgemeinschaft, the European Community-Research Infrastructure Activity , the United Kingdom Science and Technology Facilities Council and the Scottish Universities Physics Alliance, the United States Department of Energy and the National Science Foundation, and the Ministry of Education and Science of the Russian Federation. R. Milner also acknowledges the generous support of the Alexander von Humboldt Foundation, Germany.

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