

Demonstration of a novel technique to measure two-photon exchange effects in elastic $e^{\pm}p$ scattering

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Background: The discrepancy between proton electromagnetic form factors extracted using unpolarized and polarized scattering data is believed to be a consequence of two-photon exchange (TPE) effects. However, the calculations of TPE corrections have significant model dependence, and there is limited direct experimental evidence for such corrections.

Purpose: The TPE contributions depend on the sign of the lepton charge in $e^\pm p$ scattering, but the luminosities of secondary positron beams limited past measurement at large scattering angles, where the TPE effects are believed to be most significant. We present the results of a new experimental technique for making direct $e^\pm p$ comparisons, which has the potential to make precise measurements over a broad range in Q^2 and scattering angles.

Methods: We use the Jefferson Laboratory electron beam and the Hall B photon tagger to generate a clean but untagged photon beam. The photon beam impinges on a converter foil to generate a mixed beam of electrons, positrons, and photons. A chicane is used to separate and recombine the electron and positron beams while the photon beam is stopped by a photon blocker. This provides a combined electron and positron beam, with energies from 0.5 to 3.2 GeV, which impinges on a liquid hydrogen target. The large acceptance CLAS detector is used to identify and reconstruct elastic scattering events, determining both the initial lepton energy and the sign of the scattered lepton.

Results: The data were collected in two days with a primary electron beam energy of only 3.3 GeV, limiting the data from this run to smaller values of Q^2 and scattering angle. Nonetheless, this measurement yields a data sample for $e^\pm p$ with statistics comparable to those of the best previous measurements. We have shown that we can cleanly identify elastic scattering events and correct for the difference in acceptance for electron and positron scattering. Because we ran with only one polarity for the chicane, we are unable to study the difference between the incoming electron and positron beams. This systematic effect leads to the largest uncertainty in the final ratio of positron to electron scattering: $R = 1.027 \pm 0.005 \pm 0.05$ for $\langle Q^2 \rangle = 0.206 \text{ GeV}^2$ and $0.830 \leq \epsilon \leq 0.943$.

Conclusions: We have demonstrated that the tertiary e^\pm beam generated using this technique provides the opportunity for dramatically improved comparisons of $e^\pm p$ scattering, covering a significant range in both Q^2 and scattering angle. Combining data with different chicane polarities will allow for detailed studies of the difference between the incoming e^+ and e^- beams.

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I. INTRODUCTION

Electron scattering is one of the most powerful tools available for measurements involving the quark structure of nucleons and nuclei. The dominant one-photon exchange (OPE) mechanism is well understood, and the relatively weak electromagnetic coupling means that the scattering uniformly probes the matter within even a dense nucleus. This weak coupling also implies small higher-order corrections to the cross section related to two-photon exchange (TPE), which are suppressed by an additional power of the fine structure constant $\alpha \approx 1/137$. Thus, electron scattering is

the primary probe of the structure of stable hadrons, and in particular of the elastic electromagnetic form factors of the proton [1–3].

There is renewed interest in two-photon exchange contributions due to new polarization measurements of the proton electromagnetic form factors, $G_E(Q^2)$ and $G_M(Q^2)$. High- Q^2 measurements using recoil polarization techniques to extract the ratio $\mu_p G_E/G_M$ [4–6] indicated a significant discrepancy [7] with extractions based on the Rosenbluth separation technique [8–11]. This led to the concern that TPE corrections to the cross section may be more important than previously thought [12–14], with implications for not only the form factors but also other precision measurements using electron scattering [15–20].

Theoretical investigations suggest that the TPE contributions may be sufficient to resolve the discrepancy [21–23]. For the most part, the calculations indicate that the TPE effects are small but have a significant angle dependence, increasing in magnitude at larger scattering angles. Because the charge form factor, $G_E(Q^2)$, is related to the angular dependence of the elastic cross section, the impact of small TPE corrections can be very large if the angular

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dependence associated with G_E becomes small, e.g., at large Q^2 values. Thus, the charge form factor is a special case with exceptional sensitivity to TPE corrections. Nonetheless, other high-precision measurements may still need to evaluate these small contributions, and there are essentially no direct measurements of TPE that can be used to validate these calculations.

There is clear evidence for TPE contributions in other processes and other observables [24–28], but little direct evidence for TPE contributions in the unpolarized elastic electron-proton cross section. The cleanest and most direct way to study TPE contributions to the cross section is through the comparison of electron and positron scattering [29,30]. The interference between the single-photon exchange and the TPE diagrams yields the largest TPE contribution to the cross section, and its sign depends on the sign of the lepton charge. Most other radiative corrections are identical for electron and positron scattering, with the only other charge-dependent contribution being from the interference between lepton and proton bremsstrahlung, which is relatively small at low Q^2 where the proton momentum is small.

The main difficulty in measuring TPE contributions in fixed-target experiments is that the low luminosities of the secondary positron beams have historically limited measurements to regions where the cross section is large: low Q^2 and/or very forward angle scattering. The TPE contributions needed to explain the form factor discrepancy are relatively small, and become important at larger Q^2 and scattering angles. Thus, a significant increase in the luminosity is required to make meaningful measurements in the kinematic region of interest.

We present here the results from an experiment that used a novel technique to make a simultaneous measurement of positron-proton and electron-proton elastic scattering. While the data from this brief run are limited to low Q^2 and small scattering angles, the experiment provides statistics comparable to the best previous measurements. It also demonstrates the possibility of covering a large range of Q^2 and scattering angles with the precision and accuracy necessary to determine whether TPE corrections can explain the observed form factor discrepancy. Such data can also constrain calculations of the corrections at low-to-moderate Q^2 values, allowing validation of the calculations that may be needed to evaluate potential TPE impacts beyond elastic scattering.

II. TWO-PHOTON EXCHANGE

Figure 1 shows the Born contribution and higher-order QED corrections to lepton-proton elastic scattering. The TPE contribution [Figs. 1(e) and 1(f)] is difficult to calculate because the intermediate hadronic state must be integrated over all baryonic resonance and continuum states that can be excited by the virtual photon. Therefore, TPE is typically neglected in calculating radiative corrections [31–33], with the exception of the contribution needed to cancel infrared divergences in bremsstrahlung terms.

A direct measurement of the TPE correction can be achieved experimentally in the ratio of the positron-proton to electron-proton elastic cross sections. When neglecting bremsstrahlung terms, the Born term and first-order

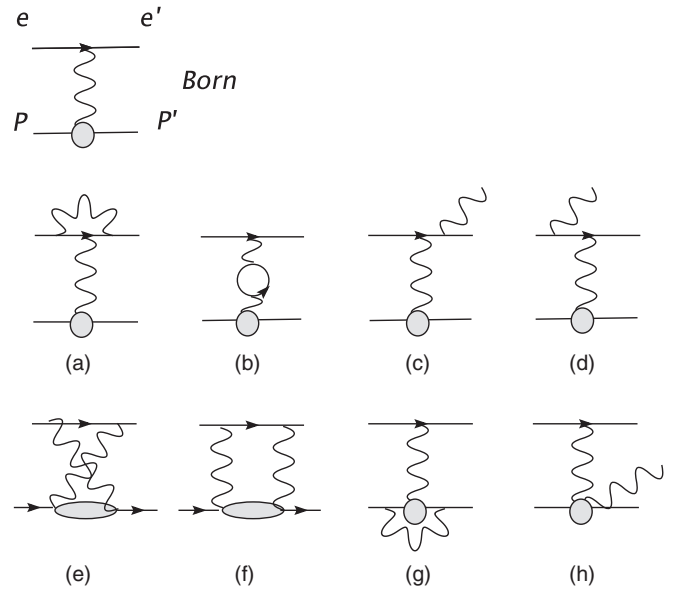


FIG. 1. Feynman diagrams for the elastic lepton-proton scattering, including the first-order QED radiative corrections. Diagram (a) shows the electron vertex renormalization term, diagram (b) shows the photon propagator renormalization term, diagrams (c) and (d) show the electron bremsstrahlung terms, diagram (g) shows the proton vertex renormalization term, diagram (h) shows the proton bremsstrahlung term, and diagrams (e) and (f) show the two-photon exchange terms, where the intermediate state can be an unexcited proton, a baryon resonance, or a continuum of hadrons.

corrections from Fig. 1 yield a total amplitude for $ep \rightarrow ep$ scattering of

$$A_{ep \rightarrow ep} = q_e q_p [A_{1\gamma} + q_e^2 A_{e,\text{vertex}} + q_p^2 A_{p,\text{vertex}} + q_e^2 A_{\text{loop}} + q_e q_p A_{2\gamma}], \quad (1)$$

where q_e and q_p are the lepton and proton charges and the amplitudes $A_{1\gamma}$, $A_{e,\text{vertex}}$, $A_{p,\text{vertex}}$, $A_{e,\text{loop}}$, and $A_{2\gamma}$ respectively describe one-photon exchange, electron and proton vertex corrections [Figs. 1(a) and 1(g)], loop corrections [Fig. 1(b)], and two-photon exchange [Figs. 1(e) and 1(f)]. Squaring the above amplitude and keeping only the corrections up to order α , we have

$$|A_{ep \rightarrow ep}|^2 \approx e^4 [A_{1\gamma}^2 + 2e^2 A_{1\gamma} \Re(A_{\text{loop}+\text{vertex}}) + 2q_e q_p A_{1\gamma} \Re(A_{2\gamma})], \quad (2)$$

where we have simplified the expression by replacing q_e^2 and q_p^2 with e^2 and taken $A_{\text{loop}+\text{vertex}}$ to be the sum of the first-order corrections where the lepton (and proton) charges appear in even powers and thus are identical for electron and positron scattering. Note that because $A_{1\gamma}$ is real and large compared to the other terms in Eq. (1), the contribution from the imaginary part of $A_{2\gamma}$ has a negligible contribution to the squared amplitude, and it is common to include only the real part of the TPE amplitude.

Experimentally, one cannot always separate true elastic scattering from events with a radiated photon in the final state. A cut on the missing energy or the invariant mass is often used to exclude events with a high-energy photon in the final

state from the case with low-energy reactions. The interference between electron and proton bremsstrahlung yields another contribution that changes sign with the lepton charge, yielding a final cross section that is proportional to

$$|A_{ep \rightarrow ep}|^2 = e^4 \{ A_{1\gamma}^2 + 2e^2 C_{\text{even}} + 2qe q_p [A_{1\gamma} \Re(A_{2\gamma}) + \Re(A_{e.br.}^* A_{p.br.})] \}, \quad (3)$$

where C_{even} is the sum of the charge-even part of the radiative contributions, including both the loop and vertex diagrams and the charge-even contributions from the electron and proton bremsstrahlung diagrams [Figs. 1(c), 1(d), and 1(h)]. There is no interference between the Born term and the bremsstrahlung terms because they have different final states. The only portion of the bremsstrahlung term that is not charge even is the interference between $A_{e.br.}$ and $A_{p.br.}$, the electron and proton bremsstrahlung terms.

The total charge-even radiative correction factor is then

$$\begin{aligned} \sigma &= \sigma_{\text{Born}}(1 + \delta_{\text{even}}), \\ \delta_{\text{even}} &= 2e^2 C_{\text{even}} / A_{1\gamma}^2. \end{aligned} \quad (4)$$

Two terms contribute to the charge asymmetry in elastic $e^\pm p$ scattering: the interference between the Born and two-photon exchange diagrams and the interference between electron and proton bremsstrahlung. Both of these terms have infrared divergent contributions, but these divergences cancel in the sum of the two contributions, making the QED description of the $e^\pm p$ scattering self-consistent. This interference effect for the standard kinematics of elastic $e^\pm p$ scattering experiments is dominated by soft-photon emission and results in a factorizable correction already included in the standard calculations of radiative corrections [31–33].

The ratio of $e^\pm p$ scattering cross sections can thus be written as follows:

$$\begin{aligned} R &= \frac{\sigma(e^+ p)}{\sigma(e^- p)} \approx \frac{1 + \delta_{\text{even}} - \delta_{2\gamma} - \delta_{e.p.br.}}{1 + \delta_{\text{even}} + \delta_{2\gamma} + \delta_{e.p.br.}} \\ &\approx 1 - 2(\delta_{2\gamma} + \delta_{e.p.br.}) / (1 + \delta_{\text{even}}), \end{aligned} \quad (5)$$

where δ_{even} is the total charge-even radiative correction factor and $\delta_{2\gamma}$ and $\delta_{e.p.br.}$ are the fractional TPE and lepton-proton interference contributions. Note that the sign of $\delta_{2\gamma}$ and $\delta_{e.p.br.}$ are chosen by convention such that they appear as additive corrections for electron scattering. However, the sign of these corrections is determined from the evaluation of the full expression given in Eq. (3). Typically, a correction is applied to account for the effect $\delta_{e.p.br.}$ to isolate the TPE contribution:

$$R_{2\gamma} \approx 1 - 2\delta_{2\gamma} / (1 + \delta_{\text{even}}), \quad (6)$$

where R is the measured e^+/e^- ratio and $R_{2\gamma}$ is the ratio after applying corrections for the $e-p$ interference term. The quantity $R_{2\gamma}$ corresponds to the quantity that is typically quoted by such measurements, although the notation is not always consistent.

Note that most previous extractions neglect the charge-even contributions, assuming that $R = 1 - 2\delta_{2\gamma} - 2\delta_{e.p.br.}$ and $R_{2\gamma} = R + 2\delta_{e.p.br.} = 1 - 2\delta_{2\gamma}$. Because the factor δ_{even} is typically small (20–30%) and negative, this means that assuming $\delta_{2\gamma} = (1 - R_{2\gamma})/2$ overestimates the TPE

contribution by approximately 20–30%. Because most extractions are consistent with $\delta_{2\gamma} = 0$, this rescaling of the TPE contribution has minimal effect. More significant is the fact that δ_{even} is neglected when applying the correction for the $e-p$ interference term. Because this correction is always a reduction in the ratio, typically 1–5%, this yields a systematic underestimate of $R_{2\gamma}$ up to $\sim 1\%$.

TPE corrections were extensively studied in the 1950s and 1960s. Early calculations suggested that the contributions were small [34–36], and early measurements comparing electron and positron scattering [37–45] did not observe significant TPE contributions. Therefore, most experiments have neglected the TPE corrections and typically apply an uncertainty in the radiative correction procedure of roughly 1–1.5%, dominated by the uncertainty in TPE corrections.

Two-photon exchange contributions have become a key issue in the field in the past decade as a result of a significant discrepancy between high- Q^2 polarization transfer measurements [4–6] of the proton form factor ratio G_E^p/G_M^p and Rosenbluth separation extractions [9–11] utilizing unpolarized scattering. Rosenbluth extractions generally showed that both G_E^p and G_M^p approximately follow the dipole form, $G_D = [1 + Q^2/(0.71 \text{ GeV}^2)]^{-2}$, so that the ratio G_E^p/G_M^p is constant, while polarization measurements showed the ratio decreasing linearly with Q^2 .

One possible explanation for this discrepancy is a TPE contribution to the cross section. Explaining the difference between these techniques requires an angle-dependent cross-section correction of 5–8% at large Q^2 [46–50]. However, this *assumes* that the cross-section change fully resolves the discrepancy. The form factor ratio discrepancy does not provide significant cross-section constraints at low Q^2 .

Calculations of the TPE corrections were revisited [12–14] in the wake of the form-factor discrepancy and initial calculations of the TPE correction brought the Rosenbluth results into near agreement with the polarization results. While low- Q^2 calculations generally agree [51–56], all of the available calculations have significant model dependence at large Q^2 . While the hadronic calculations of Blunden, Melnitchouk, and Tjon (BMT) [13,51] include only the proton intermediate state, they fully reconcile the cross-section and polarization measurements up to $Q^2 \approx 2 \text{ GeV}^2$ and resolve most of the discrepancy at higher Q^2 [21]. The effect of an intermediate Δ contribution in diagrams (e) and (f) of Fig. 1 has been estimated and has a much smaller contribution, although it may have a more significant contribution to the polarization measurements [55,57]. Calculations using a generalized parton distribution formalism [14,16], dispersion relations [54], and a QCD factorization approach [58,59] also yield TPE contributions that can resolve a large part of the discrepancy. Details of these calculations and the issues involved can be found in recent reviews [22,23].

Some limits for TPE contributions can be set based on existing cross-section and polarization measurements, combined with the known properties of the OPE and TPE contributions. In the Born approximation, the reduced cross section depends linearly on $\epsilon = [1 + 2(1 + \tau) \tan^2(\theta/2)]^{-1}$, where $\tau = Q^2/4M_p^2$. Corrections beyond single-photon

exchange can yield nonlinearities in the reduced cross section, but existing data show that the corrections are nearly linear [60–62]. A recent measurement of the ϵ dependence of the polarization transfer [63] also sets limits on TPE corrections, but the precision is not sufficient to rule out the available calculations as only the ϵ dependence, and not the overall size of the extracted form factor, can be constrained. In addition, even if there is no contribution to the polarization transfer data, there can still be a significant impact on the cross section [64,65].

It is clear that a direct confirmation of the presence of TPE corrections is needed, as well as the data necessary to validate calculations required for measurements that may be sensitive to TPE effects. Since $\delta_{2\gamma}$ is expected to be on the order of a few percent, one needs to measure R to within an uncertainty of $\sim 1\%$. While the early measurements found no significant TPE contributions [37–45], a combined analysis of these earlier experiments, based on the idea that an angle-dependent correction could reconcile the form factor measurements, gave some evidence for such a contribution [29]. The problem is that the low luminosity of the secondary beams generally limited measurement to low- Q^2 values or small angle, where TPE contributions are not expected to be larger than 1%.

There are several recent attempts to improve on previous TPE measurements comparing e^+p and μ^+p scattering. Two of these are straightforward experimentally, utilizing electron and positron beams from the VEPP-3 storage ring [66–68] or the DORIS ring at DESY [69,70]. The storage rings allow for good control of systematics, though the available luminosities limit the measurements to be done at lower beam energies and thus lower Q^2 values and also limit the statistical precision of the data at small ϵ where TPE contributions are believed to be large. The MUSE Collaboration [71] has proposed to compare e^+p and μ^+p scattering at very low Q^2 . This is motivated by the “proton radius puzzle,” the difference between proton radius extractions involving muonic hydrogen [72] and those involving electron-proton interactions [73–75]. The MUSE experiment will compare electron and muon scattering to look for indications of lepton nonuniversality, but will also examine TPE corrections, which are important in the radius extraction from electron scattering data [51,76–78].

We have taken a very different approach to comparing e^+p and e^-p scattering. Rather than alternating between monoenergetic e^+ and e^- beams, we generate a combined beam of positrons and electrons covering a range of energies and use the CEBAF Large Acceptance Spectrometer (CLAS) spectrometer in Hall B of Jefferson Laboratory to detect both the scattered lepton and struck proton. The kinematics for elastic scattering are overconstrained in such a measurement, allowing us to reconstruct the initial lepton energy as well as ensuring that the scattering was elastic. This allows a simultaneous measurement of electron and positron scattering, while also covering a wide range in ϵ and Q^2 . As such, the full experiment utilizing the setup described here [79] is the only TPE measurement that will extract the ϵ dependence of the TPE corrections at fixed Q^2 , such that they can be directly applied to Rosenbluth separations of the form factors.

III. EXPERIMENTAL DETAILS

This section and the next describe the technique used to create a mixed electron-positron beam, the methods for extracting elastic scattering events using this beam, and the initial measurement of the positron-electron elastic scattering ratio over a narrow kinematic range.

The experiment took place at the Thomas Jefferson National Accelerator Facility (Jefferson Laboratory) and used the CLAS [80] in Hall B to detect scattered particles. CLAS (see Fig. 2) is a nearly 4π detector. The magnetic field is provided by six superconducting coils that produce an approximately toroidal field in the azimuthal direction around the beam axis. The regions between the six magnet cryostats are instrumented with identical detector packages called sectors. Each sector consists of three regions of drift chambers (R1, R2, and R3) to determine the trajectories of charged particles [81], Cherenkov counters (CC) for electron identification [82], scintillation counters for time-of-flight (TOF) information [83], and electromagnetic calorimeters (EC) for electron identification and neutral particle detection [84]. The R2 drift chambers are in the region of the magnetic field and provide tracking that is then used to determine particle momenta with $\delta p/p \sim 0.6\%$. This experiment did not use the CC and used the EC only in the trigger.

We produced a simultaneous mixed beam of electrons and positrons by using the primary electron beam to produce photons and then using the photon beam to produce e^+e^- pairs (see Fig. 3). A 40- to 80-nA 3.3-GeV electron beam struck a 4.5×10^{-3} radiation-length (RL) gold radiator to produce a

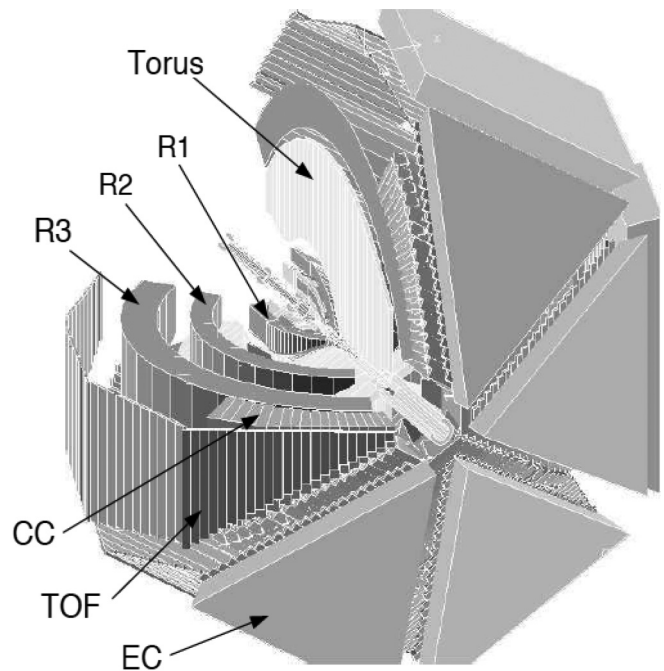


FIG. 2. Three dimensional view of CLAS showing the beamline, drift chambers (R1, R2, and R3), the Cherenkov counter (CC), the time-of-flight system (TOF), and the electromagnetic calorimeter (EC). In this view, the beam enters the picture from the upper left corner.

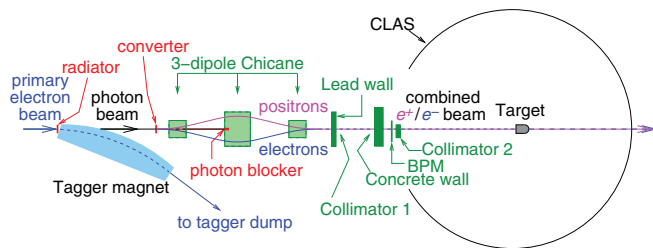


FIG. 3. (Color online) Beamline sketch for the CLAS TPE experiment. Shielding elements around the chicane and tagger are not shown. The chicane bends the electron and positron trajectories in the horizontal plane, not the vertical plane. The electron and positron directions are selected by the chicane polarity. Drawing is not to scale.

bremsstrahlung photon beam. The electrons were diverted by the Hall B tagger magnet [85] into the standard underground beam dump. The photon flux was about 10^2 greater than previous Hall B photon fluxes, requiring substantial additional shielding around the beam dump.

The photon beam passed through a 12.7-mm-diameter nickel collimator and then struck a 5.1×10^{-2} RL gold converter to produce e^+/e^- pairs. The combined photon-lepton beam then entered a three-dipole chicane to horizontally separate the electron, positron, and photon beams. The photon beam was stopped by a tungsten block in the middle of the second dipole. The lepton beams were recombined into a single beam by the third dipole, which then proceeded to a liquid hydrogen target at the center of CLAS. Figure 3 shows the layout of the beamline and Table I lists the relevant parameters.

The TPE chicane consisted of three dipole magnets. The first and third dipoles were the so-called Italian dipoles and the second dipole was the pair spectrometer magnet (PS). The Italian dipoles were operated with a magnetic field of $B \approx \pm 0.4$ T and were about 0.5 m long. They were powered in series by a single power supply. The PS had a field of $B \approx \mp 0.38$ T and was about 1 m long. The oppositely charged leptons were

TABLE I. Running conditions (i.d., inner diameter; RL, radiation length).

Parameter	Value
Primary beam	$40 \leq I \leq 80$ nA $E = 3.3$ GeV
Radiator (gold)	4.5×10^{-3} RL
Photon collimator	12.7 mm i.d. length = 30 cm
Converter (gold)	5.1×10^{-2} RL
Italian dipole	$B \approx 0.4$ T $L \approx 0.5$ m
PS dipole	$B \approx 0.38$ T $L \approx 1$ m
Lepton collimator 1 (lead)	2.5 cm i.d.
Fiber BPM	8 cm \times 8 cm
Lepton collimator 2 (lead)	6 cm i.d.
LH2 target	Diameter = 6 cm Length = 18 cm
CLAS torus current	± 1500 A

separated horizontally and recombined by the chicane. The photon beam was absorbed by a 4-cm-wide and 35-cm-long tungsten photon blocker positioned with its upstream face at the entrance aperture of the PS magnet.

The momentum acceptance of the chicane is determined by the width of the photon blocker and the apertures of the PS. The width of the photon blocker (± 0.02 m) determined the maximum lepton momentum and the PS aperture of approximately ± 0.2 m determined the minimum lepton momentum. Because the three dipoles are left-right symmetric, the two lepton beams should be identical. The final lepton beam energy ranged from approximately 0.5 to 3.2 GeV.

Either of the separated lepton beams could be blocked by inserting one of the two “beam blockers” as the beam was diverging. These are standard-sized lead bricks that could be inserted at the exit of the first Italian dipole. They were used to block either lepton beam to allow study of the other beam by itself.

We built two large shielding structures (not shown in Fig. 3), one between the first and second chicane magnets and one between the second and third chicane magnets. This shielding reduced the background produced by the chicane that would otherwise strike the CLAS detectors. We placed a 1-m by 1-m by 0.1-m thick lead wall immediately after the chicane to further reduce chicane backgrounds. This wall had a 2.5-cm-diameter collimator (“collimator 1”) to allow the mixed lepton beams through. We added other shielding, including a large concrete wall approximately 2 m upstream of the entrance to CLAS.

We measured the position of the lepton beams using a scintillating-fiber beam position monitor (BPM). This BPM is an array of 16×16 scintillating fibers read out by a multichannel photomultiplier tube (PMT) and was located approximately 15 cm upstream of the entrance to CLAS. The fibers were 1 mm \times 1 mm and had a spacing of 5 mm. We used the BPM to monitor the width and position of the lepton beams continuously during the measurement. A second collimator with a 6-cm-diameter aperture was positioned right after the BPM.

This experiment was primarily an engineering test run to determine the feasibility of using this mixed electron-positron beam line to definitively measure the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ to resolve the proton form factor discrepancy. Prior to the data-taking phase of the test run we varied the experimental parameters to optimize the lepton beam luminosity. The beam luminosity was limited by requiring that the CLAS drift chamber occupancy in each sector and each region be less than 3%. We varied the incident beam current, the radiator thickness, the photon collimator diameter, the converter thickness, the chicane magnet currents, and the first lepton collimator diameter. We also greatly improved the shielding. The values listed in Table I show the final optimized values.

For example, in order to make sure that both lepton beams had the same centroid position, we varied the current in the Italian dipole magnets while keeping the PS dipole current fixed. We blocked one lepton beam and measured the position of the centroid of the other beam as a function of the Italian dipole current. We then blocked the other beam and repeated the measurement for the first beam. Figure 4 shows the results. We fit straight lines to the linear parts of the beam position vs magnet current data. The intersection of the two linear fits indicates the Italian dipole magnet current that optimized

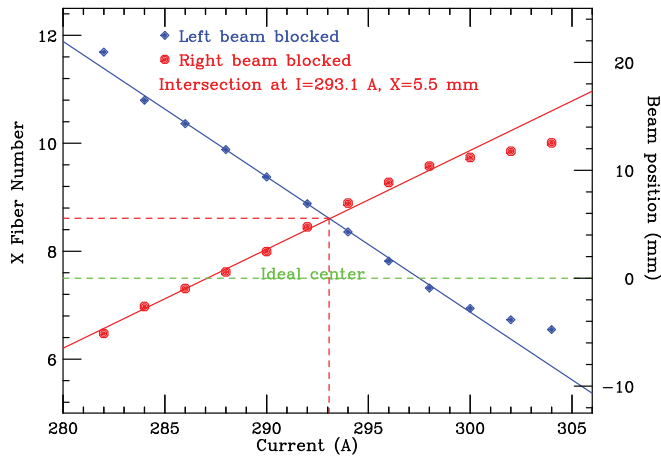


FIG. 4. (Color online) Position of the individual lepton beams as a function of the current in the first and third dipoles. Data points are measured beam centroid positions at the fiber detector and the lines are fits to points 2–10.

the centering of the two lepton beam spots. This optimized centering is approximately 5 mm off the expected beam center, indicating a likely misalignment of the BPM.

The reconstructed beam energy distribution for elastic scattering events detected in CLAS is shown in Fig. 5. The beam energy can be determined using the three-momenta of the detected lepton-proton pair, as discussed later. The measured distribution is a convolution of the incident beam energy distribution, the elastic scattering cross section, and the CLAS acceptance. The figure shows the measured distribution divided by the elastic-scattering cross section in order to reproduce a good approximation to the incident beam energy distribution. The maximum flux is at low energies, consistent with the bremsstrahlung cross section. This feature limits the measurement here to low Q^2 and high ϵ . We estimate the integrated beam current of each beam to be on the order of 1 pA. The width of the beam varied as a function of energy from an rms of 1.6 cm for beam energies in the range

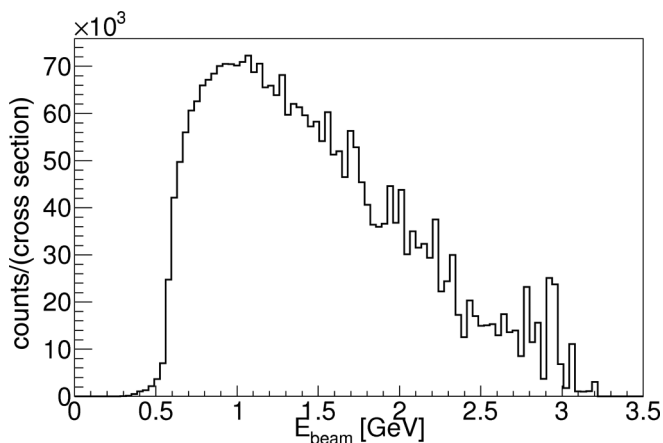


FIG. 5. Reconstructed beam energy (electrons and positrons combined) at the target for elastic events detected in CLAS. Each event is weighted by one over the elastic cross section to recover the initial beam energy distribution.

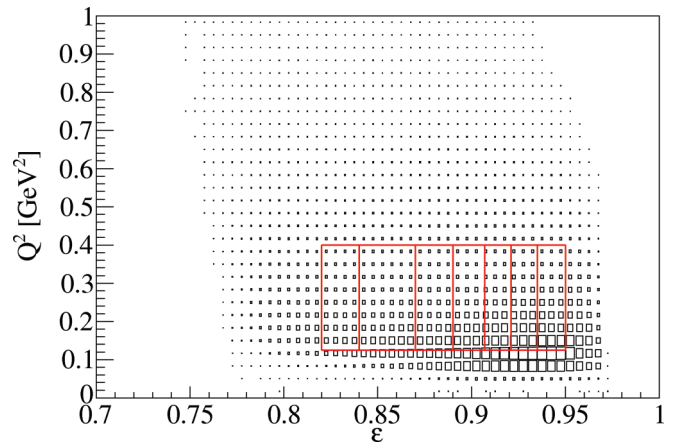


FIG. 6. (Color online) The experimental acceptance in momentum transfer and virtual photon polarization shown for negative torus polarity and both lepton charges. The red boxes show the binning for the data presented here.

$0.5 \leq E_{\text{beam}} \leq 1.0$ GeV to 1.1 cm for $2.5 \leq E_{\text{beam}} \leq 3.0$ GeV. The lepton beam was incident on a 6-cm-diameter cylindrical target of liquid hydrogen. The target had hemispherical endcaps, kapton walls, and a total length of 18 cm.

The scattered leptons and protons were detected in the CLAS spectrometer. The CLAS event trigger required a particle to deposit some energy in the EC in any sector (the threshold was chosen to accept minimum ionizing particles) and a hit in a TOF counter in the opposite sector.

The magnetic fields of the CLAS torus magnet and the beamline chicane can be reversed periodically to reduce lepton charge-dependent experimental asymmetries. However, during this run only the CLAS torus field was reversed. By using simultaneous mixed electron-positron beams we eliminated the effect of time-dependent detector efficiencies. By taking data with both chicane polarities, we would eliminate, within uncertainties, any flux-dependent differences between the left and right beams.

The data were taken as part of a test run to verify the feasibility of the experiment. The test run was sufficiently successful that we took about 1.5 days of experimental data after commissioning the e^+e^- beamline. These data allowed us to test our data analysis techniques and to measure the ratio R at low Q^2 and high ϵ as shown in Fig. 6.

IV. DATA ANALYSIS

This analysis confronted us with a number of issues uncommon to other CLAS experiments. The primary problems were (a) determining the energy of the incident lepton, (b) making the analysis lepton-charge-independent, and (c) identifying the lepton and proton without using the Cherenkov counter because its efficiency depends on whether the lepton bends in or out. Our solution to this was to require the detection of both the proton and the lepton in each event, to exploit the restricted kinematics of elastic-scattering to identify elastic events, and to match the detector acceptances for the two types of events (electron-proton and positron-proton). A description of the important analysis procedures is given below.

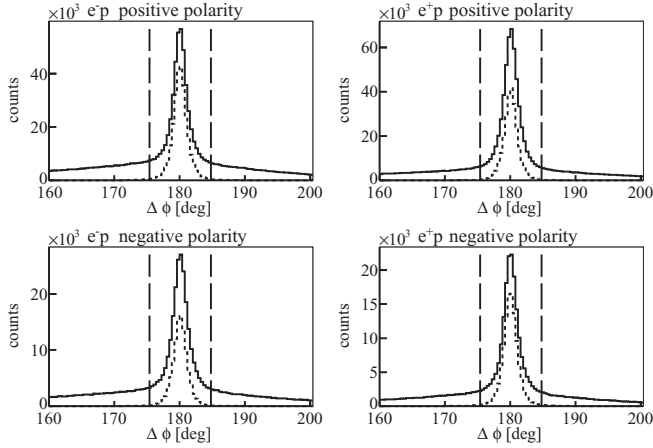


FIG. 7. Angle between lepton and proton ($\Delta\phi$) distributions for event type and torus polarity as indicated. The solid histogram is the data with only the opposite sector cut. The dotted histogram is after all other cuts. The dashed lines show the $\Delta\phi$ cut.

A. Elastic event identification

We first selected events with only two detected charged particles in opposite sectors and where their charges were either positive-negative or positive-positive.

For positive-positive events, we used information from the TOF counters to determine which particle was the proton and which was the positron. We initially identified the positron by requiring that $\beta = v/c > 0.9$, noting that at these kinematics protons have $\beta < 0.9$. With this loose particle identification (PID) cut in place we then verified the PID assignment by following the rest of the elastic event identification chain. If the event did not subsequently satisfy the elastic scattering cuts listed below, we swapped the identities of the two positive particles and checked to see if the event then satisfied the elastic cuts. None of these swapped $++$ events passed the elastic cuts, indicating that the $\beta > 0.9$ requirement properly identified positrons in all cases.

The additional cuts included fiducial cuts, bad detector removal, event vertex cuts, and four elastic scattering kinematic cuts. These are summarized in the list below. As will be shown, these cuts were correlated in that any single cut had minimal effect when all of the other cuts are applied. This leads to very clean elastic event distributions with minimal background contamination. Figures 7–10 show some of the variables before and after the elastic cuts. They are shown for all four combinations of torus magnet polarity and lepton charge. Unless otherwise indicated, they show the combined data for both torus polarities.

- (1) **Bad paddle removal.** As CLAS has aged, some of the TOF detector PMTs have deteriorated and have low gain, leading to very poor efficiency. Events with particles that hit one or more of these detectors were removed from the analysis.
- (2) **Z vertex.** The particle origin along the beamline (z vertex) was reconstructed as part of the trajectory measurement. A cut was placed on z vertex to ensure that events came from the LH₂ target.

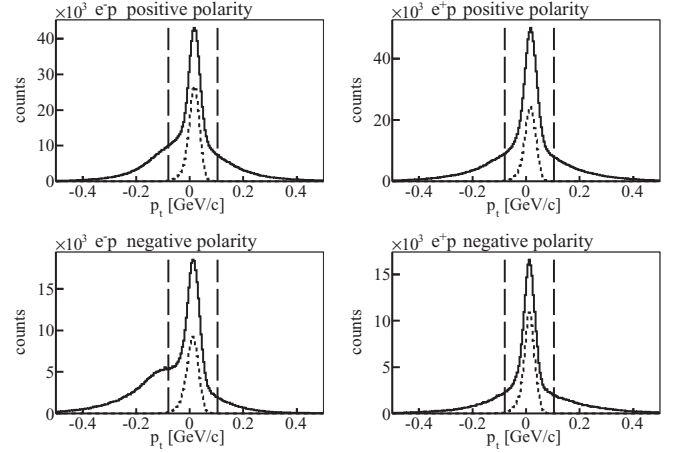


FIG. 8. Reconstructed transverse momentum distributions for event type and torus polarity as indicated. The solid histogram is the data with only the opposite sector cut. The dotted histogram is after all other cuts. The dashed lines show the p_t cut.

- (3) **Distance of closest approach between lepton and proton candidates.** This is defined as the distance between the two tracks (lepton and proton) at their closest point. A cut was placed on this distance to ensure the two tracks came from the same interaction.
- (4) **Fiducial cuts.** Fiducial cuts in angle and momentum were used to select the region of CLAS with uniform acceptance for both lepton polarities, thus matching the acceptances for electron and positron.
- (5) **Azimuthal opening angle (coplanarity).** Since there are only two particles in the final state, these events must be coplanar. Figure 7 shows the azimuthal-angle difference between events before and after all other cuts.
- (6) **Transverse momentum.** Conservation of momentum requires the total transverse momentum, p_t (with respect to the incident beam) of the final-state elastic scattering products to be zero. See Fig. 8.

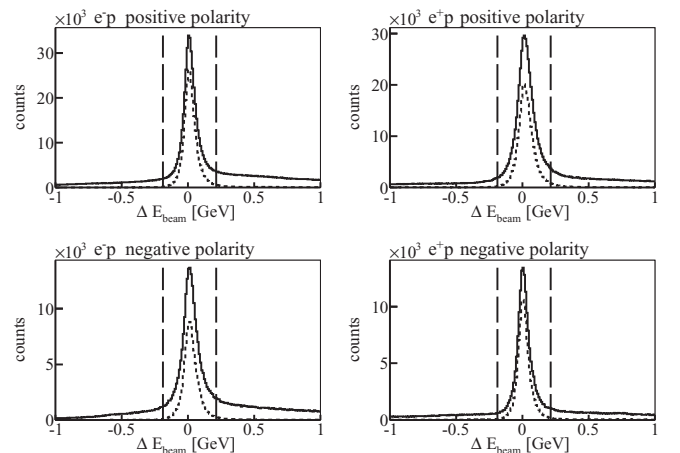


FIG. 9. ΔE_{beam} for event type and torus polarity as indicated. The solid histogram is the data with only the opposite sector cut. The dotted histogram is after all other cuts. The dashed lines show the ΔE_{beam} cut.

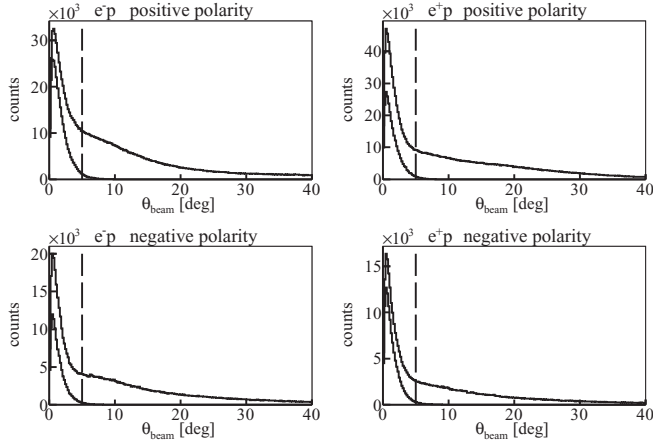


FIG. 10. Reconstructed polar angle of the beam for event type and torus polarity as indicated. The solid histogram is the data with only the opposite sector cut and the dotted histogram is after all other cuts. The dashed lines show the θ_{p_f} cut.

- (7) **Beam energy difference.** Because we measured the three-momenta for both particles in the final state, our kinematics are over constrained. This allows us to reconstruct the unknown energy of the incident lepton in two different ways. Equation (7) calculates the incident energy using the scattered lepton and proton angles, whereas Eq. (8) calculates this from the total momentum along the z direction:

$$E_{\text{beam}}^{\text{angles}} = m_p \left(\cot \frac{\theta_e}{2} \cot \theta_p - 1 \right), \quad (7)$$

$$E_{\text{beam}}^{\text{mom}} = p_e \cos \theta_e + p_p \cos \theta_p. \quad (8)$$

For elastic scattering events, these two quantities should be equal. We cut on $\Delta E_{\text{beam}} = E_{\text{beam}}^{\text{angles}} - E_{\text{beam}}^{\text{mom}}$ (see Fig. 9). The 7- to 22-MeV shift in the centroids from zero is due to particle energy loss in the target, which reduces the value of $E_{\text{beam}}^{\text{mom}}$. Note that we used $E_{\text{beam}}^{\text{angles}}$ in all calculations that depend on beam energy (e.g., Q^2 , W , ϵ).

- (8) **Momentum polar angle.** We cut on the polar angle of the final-state total-momentum ($\vec{P}_f = \vec{p}_\nu + \vec{p}_{p'}$) with respect to the z axis. Deviations from zero may be due to inelastic events, misreconstructed scattered particles, or multiple-scattered final particles. To discard these background events, we required $\theta_{p_f} < 5^\circ$ (see Fig. 10). This cut is largely redundant to the transverse momentum cut.

The cuts for items 3, 5, 6, 7, and 8 were determined by fitting a Gaussian to the peak of the combined distribution for that variable, including both event types (e^+p and e^-p) and both torus polarities and setting the cut to $\pm 4\sigma$. The widths of these distributions did not depend significantly on either torus polarity or event type.

The cleanliness of the final data sample after these cuts were applied is shown in Fig. 11, which shows the

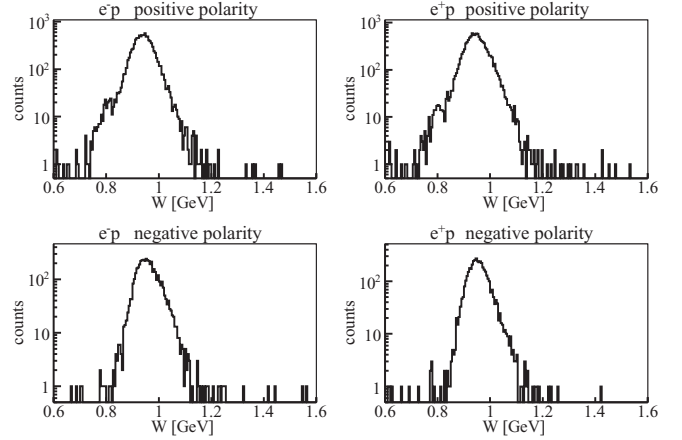


FIG. 11. Top two panels show the W distributions (in GeV) for positive torus polarity electron (left) and positron (right) events for $0.820 \leq \epsilon \leq 0.840$ and $\langle Q^2 \rangle = 0.206 \text{ GeV}^2$ with all cuts applied. The bottom two panels show the same for negative torus polarity events.

invariant mass of the virtual photon plus target proton, $W = \sqrt{m_p + 2m_p\nu - Q^2}$, distribution for one of our bins in ϵ . The peak is at the proton mass and shows virtually no hint of nonelastic background. Using side bands on either side of the peak we estimate the background to be in the range of 0.3 to 0.4%. Since the background is equal within uncertainties for both lepton species the effect on R is negligible.

The distribution of elastic events in Q^2 vs ϵ after all cuts is shown in Fig. 6. The boxes in the figure show the bins used for this analysis. The final results cover a single Q^2 bin ($0.125 \leq Q^2 \leq 0.400 \text{ GeV}^2$ with $\langle Q^2 \rangle = 0.206 \text{ GeV}^2$) and seven bins in ϵ ($0.830 \leq \epsilon \leq 0.943$) such that we have similar statistical uncertainties in each ϵ bin.

B. Acceptance matching and corrections

In order to calculate the ratio $R = \sigma(e^+p)/\sigma(e^-p)$, we must ensure that the detector acceptance does not depend on lepton charge. We first calculate R by calculating the ratio of e^+p to e^-p events for a given torus polarity. In this ratio, the proton acceptance cancels. However, the CLAS acceptances for electrons and positrons for a given kinematic bin differ because one bends away from the beamline while the other bends toward the beamline in the CLAS magnetic field.

We have accounted for acceptance differences in three steps. First, we match acceptances by using the fiducial cuts to select regions in (p, θ, ϕ) space where CLAS is almost 100% efficient in detecting both electrons and positrons. Second, we correct for differences due to dead detectors using a “swimming” algorithm to check whether an e^+p would have been detected had it been an e^-p event (and vice versa).

For example, if an e^+p event is detected and passes all the elastic cuts, then the swimming algorithm generates a conjugate lepton, in this case an e^- , with the same momentum \vec{p} as the e^+ and calculates (“swims”) its trajectory through the CLAS detector system and magnetic field. If the conjugate lepton falls within the CLAS acceptance, then the original event is kept. If the conjugate lepton falls outside of the CLAS

acceptance (either outside fiducial cuts or hits a dead paddle), the event is discarded.

In the third step, any remaining acceptance differences can be removed by measuring R for both torus polarities and constructing a double ratio. The number of detected elastic events for a given torus polarity ($t = \pm$) and a given lepton charge ($l = \pm$) should be proportional to the cross section times the unknown torus-polarity-related and lepton-charge-related detector efficiency and acceptance function f_t^l :

$$N_t^l \propto \sigma(e^l p) f_t^l.$$

Thus, for one torus polarity, the simultaneously measured ratio R_t will be

$$R_t = \frac{N_t^+}{N_t^-} = \frac{\sigma(e^+ p) f_t^+}{\sigma(e^- p) f_t^-}.$$

Taking the square root of the product of the single-polarity ratios we get

$$\begin{aligned} R &= \sqrt{R_+ R_-} = \sqrt{\frac{N_+^+ N_-^+}{N_+^- N_-^-}} \\ &= \sqrt{\frac{\sigma(e^+ p) f_+^+ \sigma(e^+ p) f_-^+}{\sigma(e^- p) f_+^- \sigma(e^- p) f_-^-}} = \frac{\sigma(e^+ p)}{\sigma(e^- p)}, \end{aligned} \quad (9)$$

where by charge symmetry, one expects $f_+^+ = f_-^-$ and $f_+^- = f_-^+$. The unknown lepton acceptance functions are expected to cancel in the double ratio. The proton acceptance cancels out independently in the single ratios R_+ and R_- .

We checked the quality of the corrections described above by comparing it to two other methods. The first approach is to apply an acceptance correction to the e^+ and e^- data separately based on a full Monte Carlo (MC) study using GSIM, the GEANT-based CLAS Monte Carlo simulation that included all dead detectors. The second approach was to calculate the double ratio with no acceptance corrections at all since, in principle, all acceptances cancel out in the double ratio. We found the differences among the three values of R to be smaller than their statistical uncertainties. We used the difference between our swimming results and our MC-corrected results to estimate the dead-detector-related systematic uncertainty.

C. Systematic uncertainties

The four major categories of systematic uncertainties in this analysis are as follows:

- (1) **Luminosity differences between electrons and positrons.** In this test run we could not independently measure the lepton beam luminosities and we did not have the time to take data for both polarities of the beamline chicane magnetic field. Therefore we determined the relative luminosity uncertainty by a detailed GEANT4-based Monte Carlo study of the beam line that included all known lepton interactions. The MC study showed that the relative flux difference between positrons and electrons on the target was less than 1% for an ideal beamline. Based on survey results, the alignment of beamline elements was within 1 mm. The MC beamline simulation showed that, for a

single chicane polarity, a 1-mm change in the relative position of the collimators and magnets leads to a 5% change in the electron-positron luminosity ratio. By measuring $e^+ p$ to $e^- p$ ratios for both polarities of the beamline chicane magnetic field and by measuring the energy distribution of the individual electron and positron beams with a dedicated beamline calorimeter, we can reduce the luminosity uncertainty in future measurements to less than 1%.

- (2) **Effects of elastic event ID cuts.** This was studied by varying the widths of these cuts (from the nominal $4\text{-}\sigma$ cut to a $3\text{-}\sigma$ cut or removing the cut entirely). The differences in the final double-ratio results between the nominal and the varied cuts result in an estimated absolute uncertainty in R of 0.0040.
- (3) **Effects of fiducial cuts.** We also varied the cuts that define the good region of CLAS, again comparing the nominal double-ratio results to those with the varied fiducial cuts. The estimated absolute uncertainty in R is 0.0011.
- (4) **Acceptance (dead detector) corrections.** As previously mentioned, this was done by comparing our nominal double-ratio results (using “swimming”) to results using a MC correction. The estimated absolute uncertainty in R is 0.0071 and is the largest of our point-to-point systematic uncertainties.

The 5% luminosity-related uncertainty is a scale-type uncertainty affecting all points in the same way. The other three items represent uncorrelated point-to-point uncertainties, which added in quadrature give an overall uncertainty of 0.0083 in R .

V. RESULTS

Our final results are presented in Table II and Fig. 12. Figure 13 and Table II show the results for $R_{2\gamma}$ [Eq. (6)] after correcting the measured ratio R for the lepton-proton bremsstrahlung interference [31]. The corrections reduce the measured ratio by 0.0049 at $\epsilon = 0.830$ and decrease gradually to 0.0034 at $\epsilon = 0.943$. The uncertainty on this correction is 0.0008 and is a combination of the uncertainty in the cutoff

TABLE II. Charge asymmetry ratio and uncertainties. $\langle Q^2 \rangle$ and $\langle \epsilon \rangle$ show the average momentum transfer and photon polarization for that bin respectively, R and $R_{2\gamma}$ show the measured value of $R = \sigma(e^+ p)/\sigma(e^- p)$ before and after radiative corrections respectively, and δR_{stat} , δR_{sys} , and δR_{lum} show the statistical uncertainty, the point-to-point systematic uncertainty, and the luminosity-related systematic uncertainty respectively.

$\langle Q^2 \rangle$ (GeV ²)	$\langle \epsilon \rangle$	R	$R_{2\gamma}$	δR_{stat}	δR_{sys}	δR_{lum}
0.206	0.830	1.027	1.023	0.015		
	0.855	1.019	1.014	0.011		
	0.880	1.033	1.028	0.012		
	0.899	1.025	1.022	0.012	0.0083	0.05
	0.914	1.024	1.020	0.011		
	0.928	1.041	1.037	0.011		
	0.943	1.050	1.047	0.012		

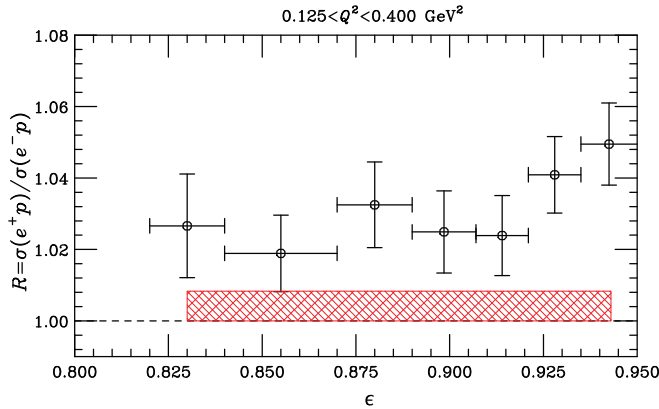


FIG. 12. (Color online) Measured ratio R for acceptance matched data at $\langle Q^2 \rangle = 0.206 \text{ GeV}^2$ before radiative corrections. Vertical error bars are statistical only and horizontal error bars show the range of the bin. The shaded band (red online) indicates the point-to-point systematic uncertainty (1σ) of the present data. The 5% luminosity-related systematic uncertainty is not shown.

value of W used in the correction calculation and the uncertainty in the term δ_{even} . This uncertainty is far smaller than our other systematic uncertainties and can be ignored. The average of our results, with the point-to-point systematic uncertainty combined in quadrature with the statistical uncertainty, is $1.027 \pm 0.005 \pm 0.05$, with the last uncertainty being due to the luminosity uncertainty.

These measurements cover a very narrow range in ϵ . $R_{2\gamma}$ is not expected to vary over this narrow range of ϵ , especially at this low momentum transfer. For example, see the BMT calculation [51] shown in Fig. 13. Therefore, the variation of these data should be consistent with its uncertainties. The standard deviation of the seven data points is 0.01, which is consistent with and slightly smaller than the statistical plus point-to-point uncertainties.

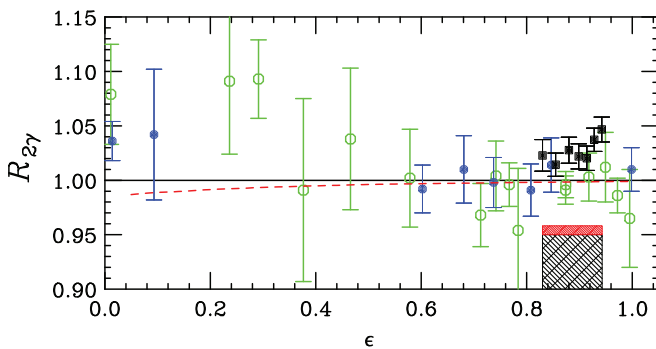


FIG. 13. (Color online) Ratio $R_{2\gamma}$ overlaid on the world data. Black filled squares are from this experiment at $\langle Q^2 \rangle = 0.206 \text{ GeV}^2$ and have had radiative corrections applied, filled circles (blue online) are previous world data at similar Q^2 , and hollow points (green online) are the rest of the previous world data with $Q^2 < 2 \text{ GeV}^2$ [29]. The densely shaded band (red online) indicates the point-to-point systematic uncertainty (1σ) and the black shaded band represents the scale-type systematic uncertainty (due to relative luminosity) on the present data. The dashed curve (red online) is the BMT calculation [51] at $Q^2 = 0.2 \text{ GeV}^2$.

We compare our results with the world's data at a similar value of Q^2 as a function of ϵ in Fig. 13. There are seven previous data points in this range of Q^2 . Our data are compatible with these points, although with significantly smaller statistical uncertainties. However, the 5% systematic uncertainty due to the luminosity prevents us from extracting any significant conclusions about the size of the TPE effect.

VI. CONCLUSION AND FUTURE PROSPECTS

We have presented a new technique for producing a mixed electron-positron beam using bremsstrahlung to produce a secondary photon beam from the primary electron beam and then pair production to produce a tertiary electron-positron beam from the photon beam. We aimed this beam at a liquid hydrogen target in the center of the CLAS spectrometer. We have presented analysis techniques to cleanly extract elastic-scattering electron-proton and positron-proton events and to minimize the charge-dependent experimental asymmetries.

We then used these techniques to extract $R = \sigma(e^+ p) / \sigma(e^- p)$, the ratio of positron-proton to electron-proton elastic scattering cross sections over a limited kinematic range at large ϵ and small Q^2 . The extracted ratio is consistent with the world's data. This ratio R is directly related to the magnitude of the two-photon exchange contribution to electron-proton elastic scattering.

During late 2010 and early 2011 we conducted the full CLAS TPE experiment using an incident beam energy of 5.5 GeV and significantly greater luminosity. This experiment covered a much larger kinematic range, up to $Q^2 = 2 \text{ GeV}^2$ and ϵ values down to about 0.3. We expect similar systematic uncertainties related to data and fiducial cuts, and dead detector corrections as were determined for the results presented here. We expect to reduce the systematic uncertainty for positron-electron luminosity differences to $\sim 1\%$ for the full run by forming an additional double ratio of results for the two different chicane polarities and by measuring the energy distribution of the individual electron and positron beams with a dedicated beamline calorimeter. Analysis of the 2010–2011 data is under way.

Two other experiments are measuring R to determine the TPE effect using electron and positron beams at internal storage rings. The Novosibirsk group [66–68] measured R at six different kinematic points and in 2012, and the OLYMPUS Collaboration [69] took data at a single lepton beam energy for $Q^2 < 2.5 \text{ GeV}^2$. These experiments have very different systematic uncertainties and kinematic coverages from the CLAS experiment.

These experiments will provide information that is vital to our understanding of the electron-scattering process as well as our understanding of the proton structure. We have heard the common statement that “the electromagnetic probe is well understood.” However, the discrepancy between Rosenbluth and polarization measurements of the form-factor ratio indicates otherwise. Indeed, if we do not understand elastic electron scattering at high precision or when higher order contributions become significant, then similar measurements will be in doubt. There are important implications for many of the nuclear physics quantities being studied ranging from

high-precision quasielastic experiments to strangeness and parity violation experiments.

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