Proton Form Factor Puzzle and the CLAS Two-Photon Exchange Experiment

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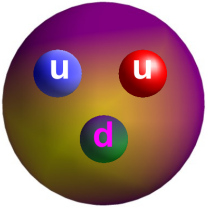
Outline

- Motivation
  - Proton Electromagnetic Form Factors and Measurements
  - Rosenbluth Separation and Polarization Transfer Methods
  - Proton Form Factor Puzzle
  - Puzzle Solver: Two-Photon Exchange Correction?
- The CLAS Two-Photon Exchange Experiment
  - Experimental Details
  - Data Analysis Methods
- Results and Discussions
- Conclusions and Outlook

Proton Form Factors

Proton

- 2 up and 1 down valence quarks + strong interaction (gluons)
- Sea of quark anti-quark pairs
- Charge and magnetization distributed over the volume → **Form Factors**



Proton Form Factors

- Fundamental observables that provide information about the composite nature of the proton
- Measure the deviation of the proton from a point-like particle
- In the non-relativistic limit, they are related to the Fourier transform of charge distribution inside proton
- Have been studied for several decades → Not yet completely understood
- Elastic electron scattering is the tool to study form factors

Elastic Electromagnetic Form Factors

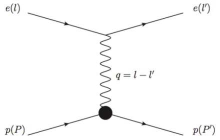
- The invariant electron-proton scattering amplitude in OPE approximation:

$$\mathcal{M}_{1\gamma} = -i\frac{e^2}{q^2} j_{\gamma\mu} J^{\mu}_{\gamma},$$

where

$$j_{\gamma\mu} = \bar{u}_e(l'_\mu)\gamma_\mu u_e(l_\mu)$$

$$J^{\mu}_{\gamma} = \bar{u}_p(P'_\mu)\Gamma^\mu(q)u_p(P_\mu).$$



- The hadronic current operator:

$$\Gamma^\mu \sim F_1(Q^2)\gamma^\mu + \frac{i\kappa\sigma^{\mu\nu}q_\nu}{2M} F_2(Q^2),$$

F_1 and F_2 are Dirac and Pauli form factors, $Q^2 = -q^2 = 4EE' \sin^2 \frac{\theta}{2}$

- The differential cross section in the lab frame:

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[\left(F_1^2 + \kappa^2 \frac{Q^2}{4M^2} F_2^2\right) + \frac{Q^2}{2M^2}(F_1 + \kappa F_2)^2 \tan^2 \frac{\theta}{2}\right]$$

$(\frac{d\sigma}{d\Omega})_{Mott} = \frac{\alpha^2 E' \cos^2\left(\frac{\theta}{2}\right)}{4E^3 \sin^4\left(\frac{\theta}{2}\right)}$ is the Mott cross section for scattering off point like particles

Elastic Electromagnetic Form Factors

- Sach's electric and magnetic form factors:

$$G_E(Q^2) = F_1 - \kappa\tau F_2$$
$$G_M(Q^2) = F_1 + \kappa F_2$$

where $\tau = \frac{Q^2}{4M^2}$ is the kinematic factor.

- As $Q^2 \to 0$: $G_E(0) = 1$ and $G_M(0) = \mu_p$ (proton magnetic moment)
- The differential cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left(\frac{1}{\varepsilon(1+\tau)}\right) \left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right],$$

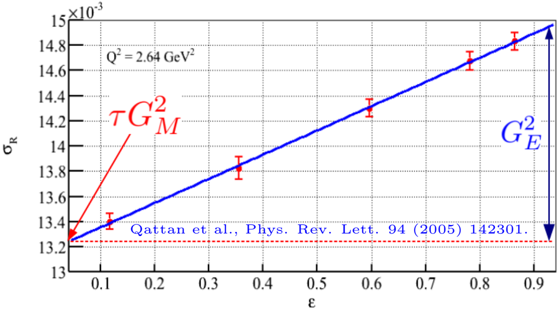
- $\sigma_R = \varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$ where:

$$\sigma_R = \left(\frac{d\sigma}{d\Omega}\right)_{lab} \left[\frac{\varepsilon(1+\tau)}{\left(\frac{d\sigma}{d\Omega}\right)_{Mott}}\right]$$

$$\varepsilon = (1 + 2(1 + \frac{Q^2}{4M^2}) \tan^2 \frac{\theta}{2})^{-1}.$$

Rosenbluth separation method

$$\sigma_R = \varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)$$



- Unpolarized electron beam is scattered off unpolarized proton target
- Measure reduced cross section (σ_R) as the function of ε at fixed Q^2
- Extract G_E and G_M contributions from the slope and intercept respectively
- At high Q^2, contributions from G_M dominates over G_E

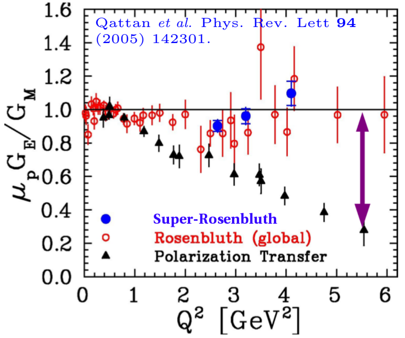
Proton Form Factor Measurements

Polarization transfer method: $p(\vec{e}, e'\vec{p})$

- Longitudinally polarized electron transfers its polarization to recoil proton.
- Transverse (P_t) and longitudinal (P_l) polarization of the recoiled proton are measured (Jones et al. Phys. Rev. Lett. 84, 1398 (2000)

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e+E'_e}{2M_p}\tan(\theta/2)$$

- Polarization transfer is a ratio measurement and has smaller systematic uncertainties

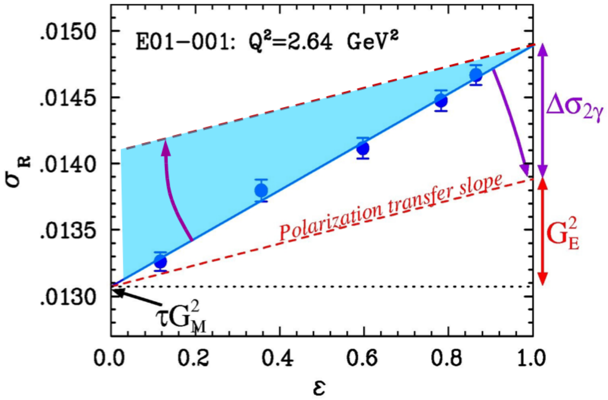


Arrington et al. Phys. Rev. C76 (2007) 035205

Puzzle

- Huge discrepancy! $\rightarrow$ Increases with Q^2
- Two methods $\rightarrow$ Two different answers!
- Both methods assume an exchange of a single virtual photon in the process
- Rosenbluth has large statistical and systematic uncertainties
- Possible explanation: Two Photon Exchange (TPE) beyond the Born Approximation
- TPE contribution expected to be $\sim 5-8\%$ at high Q^2

TPE Contribution



- Use G_M from Rosenbluth separation and G_E from polarization transfer measurement
- Additional slope must come from TPE $\Rightarrow$ 5-8 %

The general 1-γ and 2-γ exchange amplitude:

$$\mathcal{M} = \frac{e^2}{Q^2}\bar{u}(l')\gamma_\mu u(l)$$

$$1 : \times\ \bar{u}(p')\left[G_M\gamma^\mu - F_2\frac{P^\mu}{M}\right]u(p)$$

$$2 : \times\ \bar{u}(p')\left[\tilde{G}_M\gamma^\mu - \tilde{F}_2\frac{P^\mu}{M} + \tilde{F}_3\frac{\gamma\cdot K P^\mu}{M^2}\right]u(p)$$

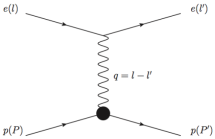
with $P = \frac{p+p'}{2}$ and $K = \frac{l+l'}{2}$
and the cross section becomes:

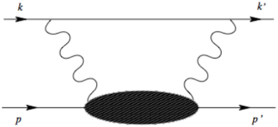
$$1 : \frac{d\sigma}{d\Omega} \propto \left[\tau G_M^2 + \varepsilon G_E^2\right]$$

$$2 : \frac{d\sigma}{d\Omega} \propto \left[\tau \tilde{G}_M^2 + \varepsilon \tilde{G}_E^2 + 2\varepsilon(\tau|\tilde{G}_M| + |\tilde{G}_E\tilde{G}_M|)Y_{2\gamma}\right]$$

$$Y_{2\gamma} \propto \mathrm{Re}\left(\frac{\tilde{F}_3}{|\tilde{G}_M|}\right)$$

Guichon and Vanderhaeghen, PRL, **91**, 142303





Thus we have:

- Another ε dependent term
- G_E and G_M are modified

Accessing the TPE Contribution

- Invariant amplitude for lepton-proton elastic scattering:

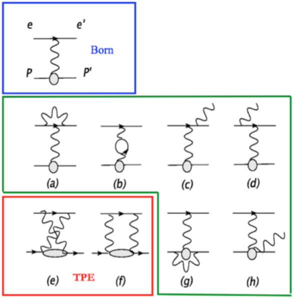
$$\mathcal{M}_{total} = q_l q_p[\mathcal{M}_{1\gamma} + q_l^2\mathcal{M}_{l.vertex} + q_p^2\mathcal{M}_{p.vertex} + q_l^2\mathcal{M}_{loop} + q_l q_p \mathcal{M}_{2\gamma}],$$

  And the cross section (to the order α^2)

$$\sigma = \sigma_{born}(1 + \delta_{even} + q_l q_p \delta_{2\gamma})$$

  δ_{even} is the lepton-charge-even radiative correction
- Additional lepton charge dependent contribution from lepton proton bremsstrahlung interference

$$\sigma = \sigma_{born}(1 + \delta_{even} + q_l q_p \delta_{2\gamma} + q_l q_p \delta_{e.p.br.}),$$



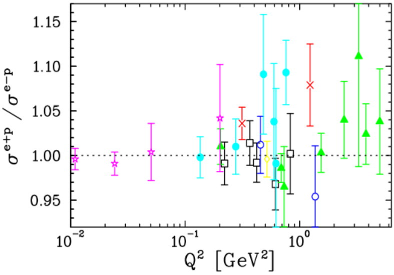
$$\frac{\sigma(e^+p)}{\sigma(e^-p)} \simeq \frac{1 + \delta_{even} - \delta_{2\gamma} - \delta_{e.p.br.}}{1 + \delta_{even} + \delta_{2\gamma} + \delta_{e.p.br.}} \simeq 1 - \frac{2(\delta_{2\gamma} + \delta_{e.p.br.})}{(1 + \delta_{even})}.$$

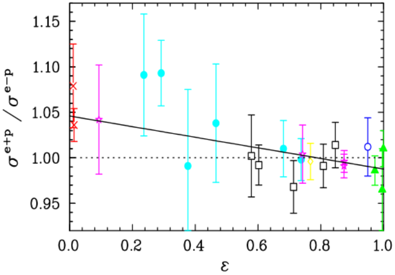
The ratio after applying charge odd radiative corrections

$$R_{2\gamma} = 1 - \frac{2\delta_{2\gamma}}{1 + \delta_{even}}$$

$R_{2\gamma}$ provides a model-independent measurement of the real part of the TPE contribution

Previous World Data

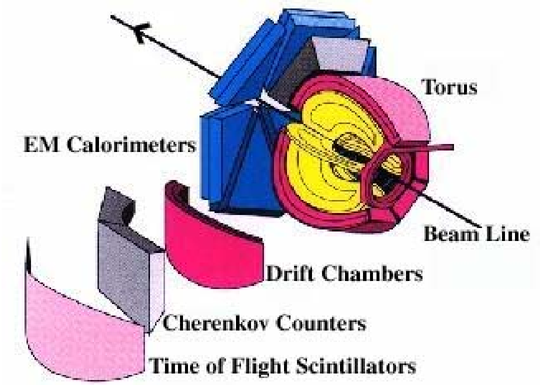




- TPE effect was measured in early 1960s $\Rightarrow$ Small effect (ignored)
- World data is not enough to resolve the discrepancy
- Can not draw any conclusion because of the size of the error bars
- Need precise measurement with wide kinematic coverage $\Rightarrow$ **CEBAF Large Acceptance Spectrometer (CLAS)**
- Other experiments measuring the ratio $\rightarrow$ OLYMPUS @ DESY, Novosibirsk @ VEPP-3

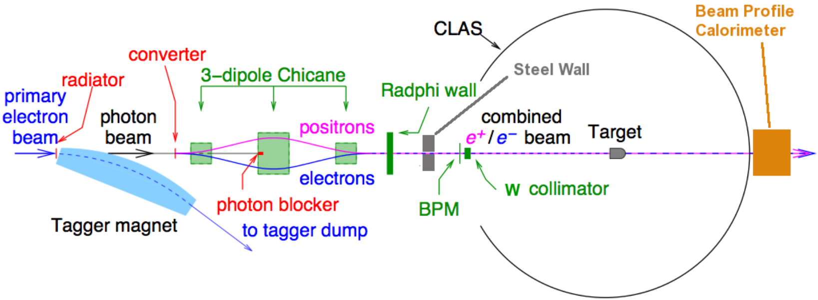
The CLAS Two-Photon Exchange Experiment

CEBAF Large Acceptance Spectrometer (CLAS)



- 4π hermetic detector, divided into six independent sectors
- Six Superconducting Coils → toroidal magnetic field → bends particle towards or away from the beamline depending upon charge
- 3 regions of Drift Chambers → for charged particle tracking
- Time of Flight Scintillators → for timing measurements
- EM Calorimeters → for energy measurements/trigger ⇒ only used in trigger by TPE
- Čerenkov Counters → electron/pion separation → optimized for in-benders → not used by TPE

Producing a Mixed Electron Positron Beam in Hall-B



- Primary electron beam: 5.5 GeV and 100-120 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: sweep the primary electrons to the tagger dump
- Converter: 9% of photons convert to electron/positron pairs
- Chicane: separate the lepton beams, stop photons and recombine the e^+ and e^- beams
- Target: 30 cm liquid hydrogen
- Detector: CEBAF Large Acceptance Spectrometer (CLAS)

Chicane Field Optimization

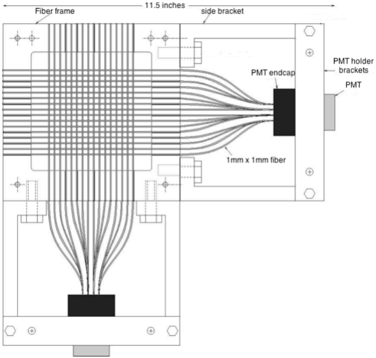
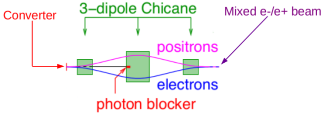
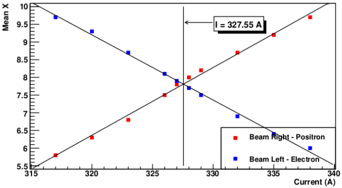


Figure: Sparse Fiber Monitor (built at FIU)

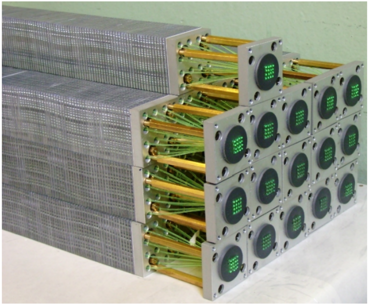


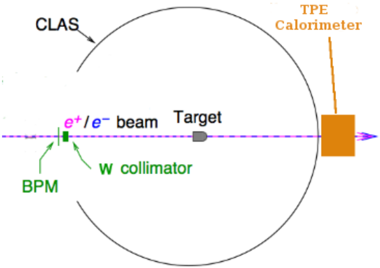


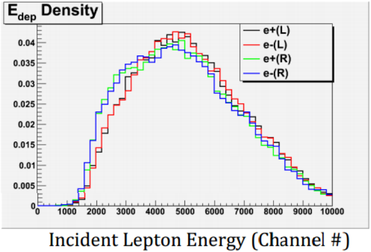
- Block one lepton beam
- Record the position of the beam at SFM varying chicane current
- Repeat for the other beam

- Repeated after each chicane flip
- Chicane current was reproducible

TPE Calorimeter

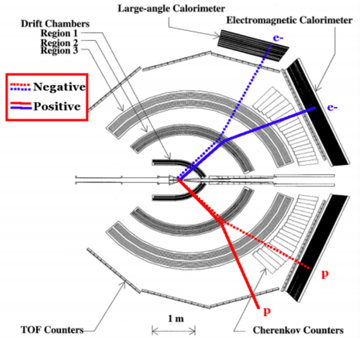


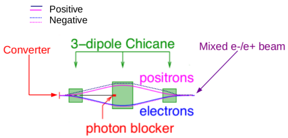




- 30 module shashlik (Pb/scint) calorimeter
- Positioned downstream of the target just outside CLAS
- Used for beam profile measurements
- Not used during regular production data taking

Experimental Features

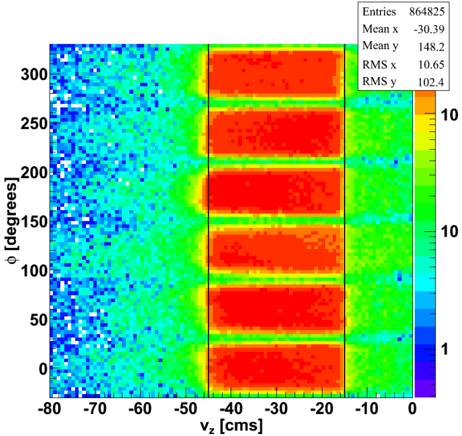




- Continuous incident energy distribution from 0 - 5 GeV
- Coincidence detection of lepton and proton at the opposite CLAS sectors
- Match acceptance
  - Select regions of CLAS with 100% acceptance for both e^+ and e^-
- Systematic controls
  - Reverse torus and chicane magnetic fields periodically to cancel artificial charge asymmetries
- Non-standard particle identification: Use elastic scattering kinematics for event selection

Elastic Event Selection

- Selected negative/positive or positive/positive charged pair in the opposite CLAS sectors
- Target vertex cut: $-45 < v_z < -15$ cm
- Co-planarity cut: $\Delta\phi = \phi_l - \phi_p$



Vertex distribution along Z-axis

Elastic Event Selection

- Use elastic scattering kinematics to reconstruct beam energy:
  - Using final lepton and proton polar angles:

$$E(\theta_l, \theta_p) = M\left[\frac{1}{\tan\frac{\theta_l}{2}\tan\theta_p} - 1\right]$$

  - Using momenta of lepton and proton:

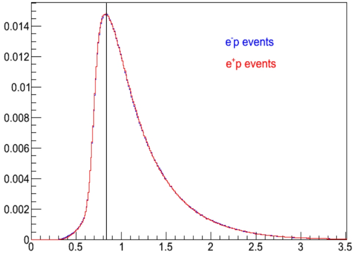
$$E(p_l, p_p) = p_l\cos\theta_l + p_p\cos\theta_p$$

  - Reconstructed beam energy difference

$$\Delta E_{beam} = E(\theta_l, \theta_p) - E(p_l, p_p)$$

  - Calculate the difference between measured and calculated momentum of the scattered lepton

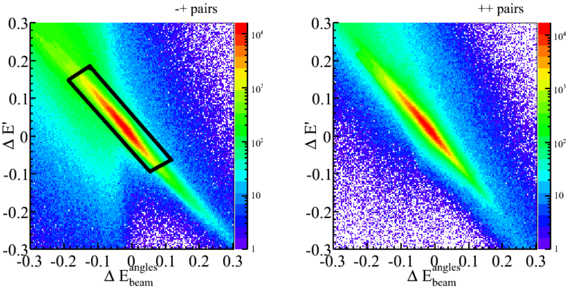
$$\Delta E_l' = E_l^{meas} - E_l^{calc}(\theta_l, \theta_p)$$



$E(\theta_l, \theta_p)$

- Identical e^+/e^- beam energy

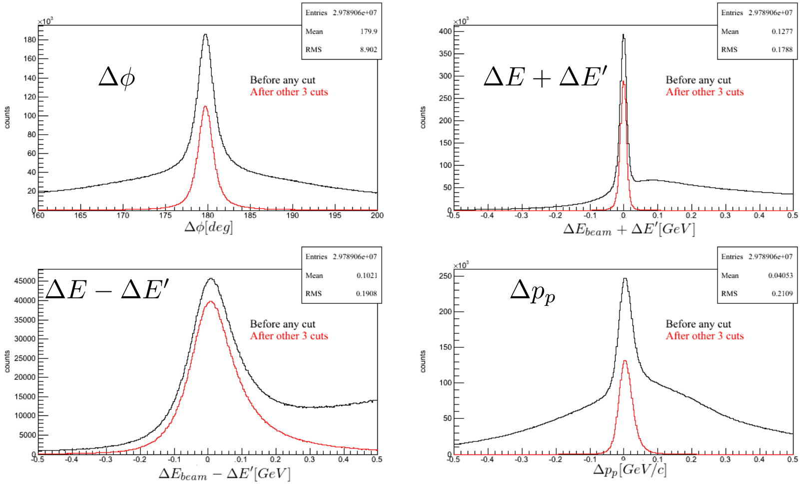
Elastic Event Selection



- ΔE_{beam} and $\Delta E_l'$ are correlated
- Cut on $\Delta E_{beam} + \Delta E_l'$ and $\Delta E_{beam} - \Delta E_l'$
- Cut on the difference between measured and calculated momentum of the recoil proton

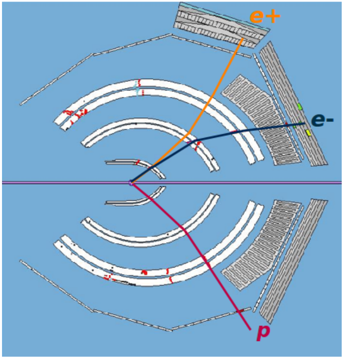
$$\Delta p_p' = p_p^{meas} - p_p^{calc}(\theta_l, \theta_p)$$

Kinematic Cuts Summary

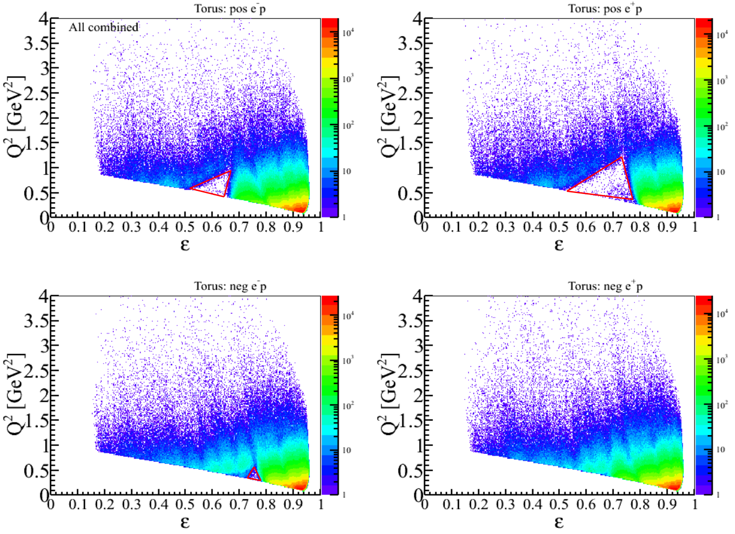


Dead Detector Cuts (Acceptance)

- Fiducial cuts to select regions in (p, θ, ϕ) with same detection efficiency for both e^+ and e^-
- Remove inefficient TOF paddles
- Several dead regions in sector 3 forward region $\rightarrow$ Removed if lepton/proton hits sector 3 forward region
- Employ swimming algorithm:
  - For each detected elastic $e^{\pm}p$ event, generate a conjugate lepton with the same vertex and momentum
  - Swim both original and the conjugate lepton through CLAS
  - Accept the event only if the original lepton and its conjugate both hit the active region of the detector

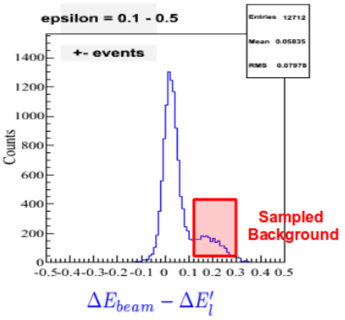


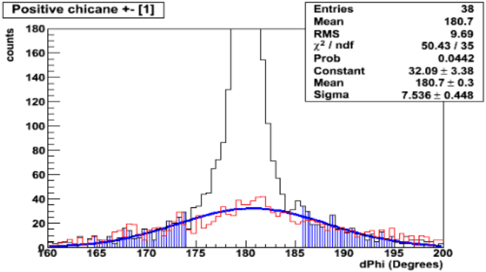
Kinematic coverage (Q^2 vs. ε)

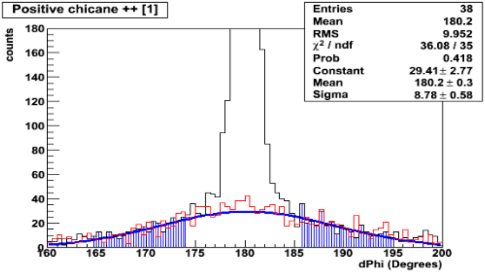


Trigger requires at least one particle in the forward ($\theta < 45°$) region of CLAS

Background Subtraction







- Sample background from the $\Delta E - \Delta E'$ tails, plot on $\Delta\phi$
- Fit $\Delta\phi$ distributions with Gaussian
- Sampled = Fit
- Use fit background for all kinematics since sampling fails at other kinematics due to peak width
- Subtract background from the peak

Cross section Ratio

- The number of detected elastic events:

$$N_t^l \propto \sigma(e^l p) A_t^l A_t^p,$$

where l is the sign of lepton charge, A_t^l and A_t^p are the lepton and proton acceptance in torus polarity t

- Take a ratio of e^+p to e^-p elastic events for the given torus and chicane $\Rightarrow$ Proton acceptance cancels

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

- Take the square root of the product of individual torus ratios for the given chicane polarity to form a double ratio $\Rightarrow$ Lepton acceptance cancels

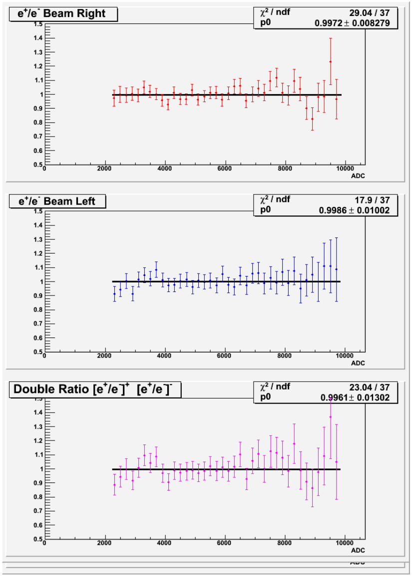
$$R^c = \sqrt{(R_+^c R_-^c)} = \sqrt{\frac{N_+(e^+p)}{N_+(e^-p)} \frac{N_-(e^+p)}{N_-(e^-p)}} = \sqrt{\frac{\sigma(e^+p) A_+^+}{\sigma(e^-p) A_+^-} \frac{\sigma(e^+p) A_-^+}{\sigma(e^-p) A_-^-}}$$

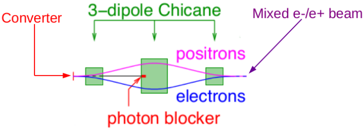
By charge-symmetry $A_+^+ = A_-^-$ and $A_+^- = A_-^+$

- Take the square root of the product of individual chicane double ratios to form a quadruple ratio $\Rightarrow$ Beam asymmetry cancels

$$R_q = \sqrt{(R^+ R^-)}$$

electron/positron Luminosity

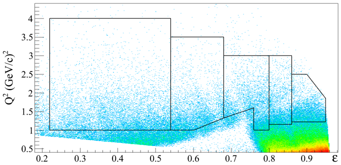




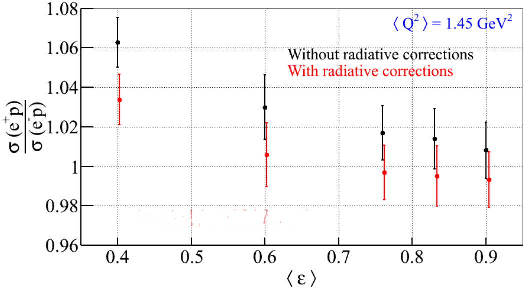
- e^+/e^- pair-production is inherently charge-symmetric
- e^+-left is the same as e^--left $\rightarrow$ periodically flipping the chicane leads to symmetric luminosities
- Calorimeter data before and after each chicane flip to measure relative left/right e^+/e^- flux
- Any remaining effects are estimated in systematic uncertainties

RESULTS

Results (high Q^2)

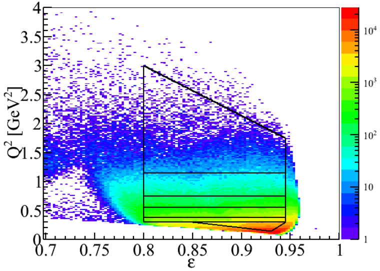


- Average Q^2 of the bins ≈ 1.5 GeV/c^2
- Background subtracted
- Dead detector cuts applied
- With charge-odd bremsstrahlung radiative corrections

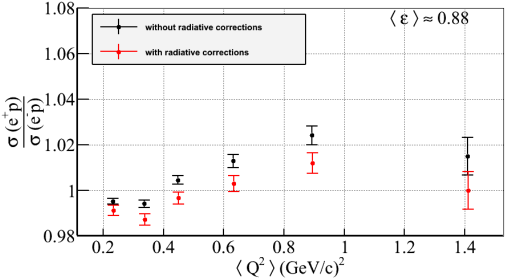


D. Adikaram, Ph.D. Thesis, Old Dominian University (2014).

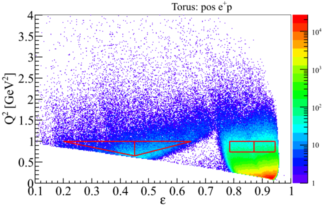
Results (high ε)



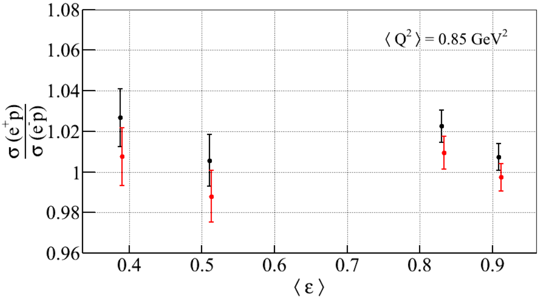
- Average $\varepsilon \approx 0.88$
- Negligible background at high ε
- Background subtracted
- Dead detector cuts applied
- With charge-odd bremsstrahlung radiative corrections



Results (low Q^2)



- Average Q^2 of the bins ≈ 0.85 GeV^2
- Background subtracted
- Dead detector cuts applied
- With charge-odd bremsstrahlung radiative corrections

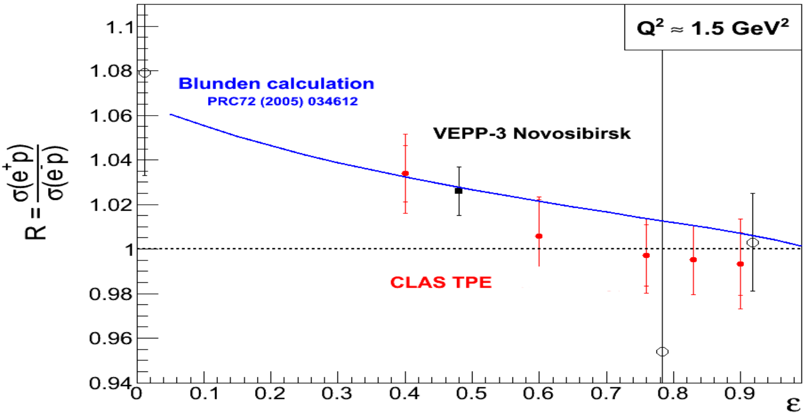


Systematic Uncertainties

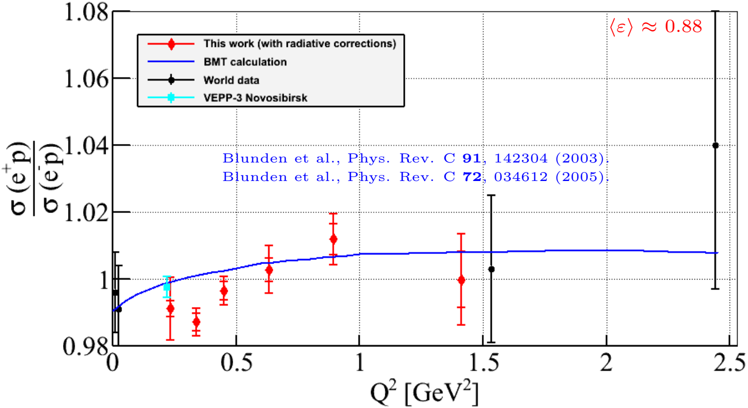
- electron/positron Luminosity
  - Estimated from the ratio variance with different magnet cycles
- CLAS imperfections
  - Estimated from the ratio variance with CLAS sectors
- Background subtraction
- Elastic event selection cuts
- Fiducial cuts
- Target vertex cuts

Comparison to the world data at $Q^2 > 1$ GeV/c^2

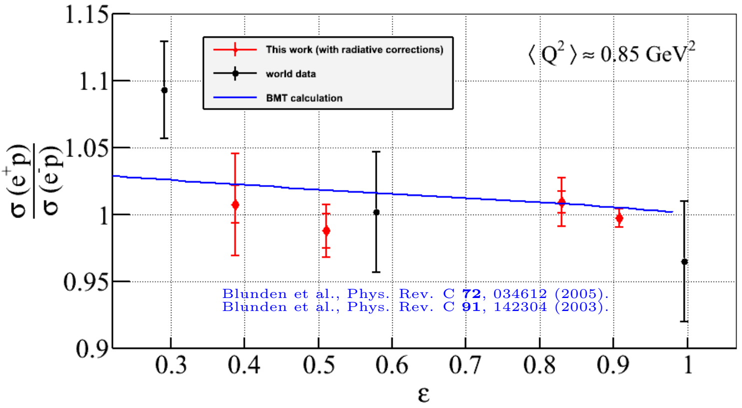
D. Adikaram, Ph.D. Thesis, Old Dominian University (2014).



Comparison to the world data at $\varepsilon \approx 0.9$



Comparison to the world data at $Q^2 \approx 0.85$ GeV^2



Summary

- Significant discrepancy exists between Rosenbluth and polarization transfer measurements of the proton electric to magnetic form factor ratio ($\frac{G_E}{G_M}$)
- The proposed explanation is the effect of the two-photon exchange beyond the Born approximation
- $\frac{\sigma(e^+p)}{\sigma(e^-p)}$ provides a model independent measurement of the TPE effect
- CLAS TPE experiment measured $\frac{\sigma(e^+p)}{\sigma(e^-p)}$ over a wide range of Q^2 and ε with significantly better precision than previous measurements
- In the kinematics of the experiment, our results are in agreement with the hadronic TPE calculations by Blunden, Melnitchouk, and Tjon
- Analysis note is under review by the CLAS Collaboration
- Other experiments (OLYMPUS, Novosibirsk) are also analyzing their data to extract the ratio at $Q^2 < 2.5$ GeV^2
- Results from the CLAS TPE and other experiments provide vital information required to reconcile Rosenbluth and polarization transfer measurements
- Measurements at higher Q^2, where the discrepancy is larger, are necessary to completely resolve the form factor discrepancy

Thank You

Backup slides