Beyond the Born Approximation
Measuring the Two Photon Exchange Correction at CLAS

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CLAS Collaboration

Experimental and Theoretical Aspects of Proton Form Factors
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1. Physics Motivation
2. TPE
3. Experiment
4. Analysis overview
5. Summary
Elastic Scattering: Born Approximation

\[ \Gamma^\mu(q) = \gamma^\mu F_1(q^2) + \frac{1}{2M_N} \sigma^{\mu\nu} q_\nu F_2(q^2) \]

- \( F_1(q^2) \): Non-spin flip Dirac Form Factor
- \( F_2(q^2) \): Spin flip Pauli Form Factor

**Nucleon Current Operator** \( \Gamma^\mu(q) \)

**ep Kinematics**
- \( k \) (\( k' \)): incoming (outgoing) lepton 4-vector
- \( P \) (\( P' \)): incoming (outgoing) proton 4-vector
- Single virtual photon:
  \[ q^2 = (k - k')^2 = -Q^2, \quad Q^2 > 0 \]
- Proton remains in tact

**\( F_1 \) and \( F_2 \) are NOT unique**

- Electric form factor:
  \[ G_{EP}(Q^2) = F_1^P(Q^2) - \tau \kappa F_2^P(Q^2) \]
- Magnetic form factor:
  \[ G_{MP}(Q^2) = F_1^P(Q^2) + \kappa F_2^P(Q^2) \]

\[ \tau = \frac{Q^2}{4M_P^2} ; \quad G_{EP} \mu_P \approx G_{MP} \approx G_D \]
The Proton Formfactor Puzzle

- **Rosenbluth Separation**: (SLAC, MIT BATES, JLab et al.)

\[
\sigma_r = \left( \frac{d\sigma}{d\Omega} \right) \left[ \frac{\varepsilon(1 + \tau)}{\sigma_{mott}} \right] = \tau G_M^2 + \varepsilon G_E^2
\]

\[
\varepsilon = \left[ 1 + 2(1 + \tau) \tan^2 \theta_e / 2 \right]^{-1} \quad \tau = \frac{Q^2}{4M^2}
\]

- Separate \( G_E \) and \( G_M \) contributions at a particular \( Q^2 \) using different beam energies and scattered electron angles
- \( G_M \) measurement dominates at high \( Q^2 \), \( G_E \) is suppressed

- **Polarization Transfer**: (Hall A & C)

\[
\frac{G_E}{G_M} = - \frac{P_t}{P_l} \frac{(E_e + E_e')}{2M} \tan \frac{\theta_e}{2}
\]

- Longitudinal polarized electrons incident on proton target
- Measure transverse and longitudinal polarization of recoiled proton
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- Longitudinal polarized electrons incident on proton target

- Measure transverse and longitudinal polarization of recoiled proton
Use $G_M$ from Rosenbluth Separation and $G_E$ from Polarization Transfer

To account for the difference we need a $\varepsilon$ dependent correction to the cross section on the order of a few percent
The general $1 - \gamma$ and $2 - \gamma$ exchange amplitudes

$$A = \frac{e^2}{Q^2} \bar{u}(k') \gamma^\mu u(k)$$

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

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

The general $1 - \gamma$ and $2 - \gamma$ exchange cross section

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

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

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

Guichon and Vanderhaeghen, PRL 91 (03) 142303
Predictions

Model Dependent Predictions

pQCD

GPD

Baryonic

TPE effect small

TPE effect sizeable

Q^2 = 3.0 (GeV/c)^2

D. Borisuk, A. Kobushkin, PRC74 (2008) 0565203


Positrons to the rescue!

- The Born amplitude changes sign as the charge of the incident beam.
- The leading TPE terms of the elastic scattering cross section are sensitive to the lepton charge.

The elastic $e^\pm p \rightarrow e^\pm p$ scattering contribution:

$$
\sigma(e^\pm) \propto |A_{\text{born}} + \cdots \pm A_{2\gamma}|^2
$$

$$
\sigma(e^\pm) \propto |A_{\text{born}}(\alpha)|^2 \pm 2A_{\text{born}}(\alpha)\text{Re}(A_{2\gamma})
$$

The ratio of the cross sections isolates the TPE correction term:

$$
R = \frac{\sigma(e^+)}{\sigma(e^-)} = 1 - 2\delta_{2\gamma}
$$

$$
\delta_{2\gamma} = \frac{2\text{Re}(A_{2\gamma})}{A_{\text{born}}}
$$

- We can calculate this very well (QED)
- Theoretical calculation of the diagram is hard: Need to integrate over all baryon states
- The $e^- p/e^+ p$ ratio measures the real part of the TPE contribution
Limited Previous $e^+p/e^-p$ Data

TPE was a known issue

- TPE expected to be on order $\alpha \sim 1\%$ effect
- Previous $e^+p/e^-p$ data consistent with this assumption
- Reanalysis of the existing world data is inconclusive, but indicates a few $\% \varepsilon$ dependence
- Negligible $Q^2$ dependence of the ratio

Continuous Electron Beam Accelerator Facility (CEBAF)

- 5 pass super-conducting accelerator
- Polarized electrons up to 6 GeV
- Maximum Current $\sim 100 \, \mu$A
- Upgrading to 12 GeV
- 3 experimental halls running (A, B, & C) (D is coming soon)
Making Positrons at CLAS

- **Primary electron beam**: 5.5 GeV and 100-120 nA
- **Radiator**: 0.9% of primary electrons radiate high energy photons
- **Tagger magnet**: Transport electrons to tagger dump
- **Converter**: 9% of photons are converted to electron/positron pairs
- **Chicane**: separate the lepton beams
  - Remaining photons are stopped at the photon blocker
  - $e^+$ and $e^-$ beams are then recombined and continue to the target
- **Target**: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- **Detector**: CLAS (DC, TOF)
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Extensive GEANT simulations of detector backgrounds.
Confirmed simulation with test run data
A lot of shielding added on tagger, tagger dump and chicane.
Improved luminosity by a $\approx$ factor 100
Beam Line Modification for TPE
Beam Profiling

TPE Calorimeter

- Measure beam energy vs position during low luminosity run
- 30 module Shashlik (Pb/Scint) calorimeter
- Located directly downstream of CLAS on the forward carriage

Fiber Monitors

- 16x16 Sparse fiber monitor continually monitoring beam profile before the target
- 64x64 Dense fiber monitor mounted on TPE Calorimeter face for beam profiling during low luminosity runs
- Bicron fibers spaced 5 mm (1mm) apart glued to a Hamamatsu PMT
- Beam size $\sim 15$ mm radius
Flipped chicane polarity about once a week
Check for geometric alignment of $e^-/e^+$ on target – Varied steering magnet currents and measured individual beam positions at sparse fiber monitor
Reproducible crossing for all chicane flips
1. Trigger on particle in forward $45^0$ and anything in opposite sector
2. Target vertex cut ($-45 \text{ cm} \leq V_z \leq -15 \text{ cm}$)
3. Momentum Corrections
4. Proton energy loss corrections
5. Fiducial Cuts
6. Swimming – Acceptance matching ++ and +- events

EC and TOF ($\theta < 45^\circ$) and opposite sector TOF
Non-Standard PID & Elastic Event Selection

1. Select ++ and +− track pairs
2. Coplanarity cut \( \phi_{proton} - \phi_{lepton} \approx 180^0 \)
3. Reconstructed Beam Energy:
   \[
   E_1 = M_P \left[ \frac{1}{\tan(\theta_e/2) \tan(\theta_p)} - 1.0 \right] 
   \]
   \[
   E_2 = P_e \cos(\theta_e) + P_p \cos(\theta_P) 
   \]
   \[
   \Delta E_{Beam} = E_1 - E_2 
   \]
4. Scattered lepton Energy:
   \[
   \Delta E'_e = E^e_{measured} - E^e(\theta_e, \theta_p) 
   \]
5. Proton Momentum:
   \[
   \Delta P(p) = P_p - \frac{P_e \sin(\theta_e)}{\sin(\theta_p)} 
   \]
   (1)
$\Delta E_{Beam}$ vs $\Delta E'_e$

$\Delta E$ and $\Delta E'_e$ are correlated, so we cut on the sum ($\Delta E+$) and difference ($\Delta E-$)
Kinematic Cuts

No cuts  Apply other 3 kinematic cuts

\[ \Delta P_p \]

\[ \Delta \phi \]

\[ \Delta \Phi \]

\[ \Delta E - \Delta E'_0 \]

\[ \Delta E + \Delta E'_0 \]

\[ \Delta E^+ \]
Ratios

1. Apply fiducial cuts to select regions where both $e^-$ and $e^+$ can both be detected.

\[ R = \frac{Y(e^+ + p)}{Y(e^- + p)} \]

\[ R_2 = \sqrt{\frac{Y(e^+ + p)Y(e^- + p)}{Y(e^+ - p)Y(e^- - p)}} \]

\[ R_4 = \sqrt{R^2 + 2R^{-2}} \]
1. Apply fiducial cuts to select regions where both $e^-$ and $e^+$ can both be detected.

2. Measure Elastic Scattering Ratio:
   Proton acceptance cancels in the ratio
   \[ R = \frac{Y(e^+P)}{Y(e^-P)} \]
**Ratios**

1. Apply fiducial cuts to select regions where both $e^-$ and $e^+$ can both be detected.

2. Measure Elastic Scattering Ratio:
   Proton acceptance cancels in the ratio
   
   $$R = \frac{Y(e^+P)}{Y(e^-P)}$$

3. Flip torus polarity: Lepton acceptance cancels in double ratio
   
   $$R_2 = \sqrt{\left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^+ \times \left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^\-}$$
Apply fiducial cuts to select regions where both $e^-$ and $e^+$ can both be detected

Measure Elastic Scattering Ratio:
Proton acceptance cancels in the ratio

$$R = \frac{Y(e^+P)}{Y(e^-P)}$$

Flip torus polarity: Lepton acceptance cancels in double ratio

$$R_2 = \sqrt{\left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^+ \times \left[\frac{Y_{e^+P}}{Y_{e^-P}}\right]^–}$$

Flip chicane polarity: Beam asymmetries cancel in quadruple ratio

$$R_4 = \sqrt{R_2^+ \times R_2^-}$$
$Q^2$ vs $\epsilon$ (TPE II 2010-2011)
$Q^2 \text{ vs } \varepsilon$ (TPE II 2010-2011)

**Trigger Holes**

- **Positive torus + events**
  - Entries: 368356
  - Mean $\mu$ = 0.2871
  - RMS $\sigma$ = 0.07479
  - RMS $\sigma_y$ = 0.2101

- **Positive torus ++ events**
  - Entries: 271486
  - Mean $\mu$ = 0.2874
  - RMS $\sigma$ = 0.06523
  - RMS $\sigma_y$ = 0.2166

- **Negative torus + events**
  - Entries: 414623
  - Mean $\mu$ = 0.2842
  - RMS $\sigma$ = 0.07306
  - RMS $\sigma_y$ = 0.2087

- **Negative torus ++ events**
  - Entries: 342487
  - Mean $\mu$ = 0.2914
  - RMS $\sigma$ = 0.07585
  - RMS $\sigma_y$ = 0.2165
Analysis Issues [In Progress]

1. High background rates 10 – 15% losses for relative timing. Will use timing for systematic error checks only.
2. Need to account for dead detector channels
   - Swimming
   - Simulations
3. Background subtraction
   - Fitted
   - Sampled
   - Mixed Events
GSIM [In Progress]
Low $\epsilon$ Bins
Background Subtraction [Method I]

- $p_1 =$ no. of events in bins $b_1$ - $b_2$ in total (signal)
- $p_2 =$ no. of events in bins $b_3$ - $b_4$ in total (signal)
- $bg_1 =$ no. of events in bins $b_1$ - $b_2$ in background
- $bg_2 =$ no. of events in bins $b_3$ - $b_4$ in background
- Scale Factor

$$S = \frac{(p_1 + p_2)}{(bg_1 + bg_2)}$$
Background Subtraction [Method I]

**Positivetorus + events**

- **h11[6]**
  - Entries: 17823
  - Mean: 180
  - RMS: 9.437
  - #chi² / ndf: 17.28 / 4
  - Prob: 0.001709
  - Constant: 1656 #pm 26.0
  - Mean: 180.2 #pm 0.9
  - Sigma: 0.9315 #pm 0.0131

**Positive torus + events**

- **h12[6]**
  - Entries: 11203
  - Mean: 180
  - RMS: 13.95

**Positivetorus + events**

- **Scaled Background**

**Positive torus + events**

- **Total - Scaled Background**

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Background Subtraction [Method II]

- Fit back ground
- Polynomial fits to wings
- Subtract fits from distribution
Define distance:

\[ d = \sqrt{N(\sigma_\phi)^2 + N(\sigma_{E+})^2 + N(\sigma_{E-})^2 + N(\sigma_{PP})^2} \]

- Mix Events
  - Pair particle from Event\textsubscript{i} with particle from Event\textsubscript{j}
  - Z-vertex, two charge and minimum energy cuts
- Scale Mixed Events
  Scalefactor = Data Area/Mixed Area
Method III: Event Mixing Low $\varepsilon$

- Define distance:
  $$d = \sqrt{N(\sigma_\phi)^2 + N(\sigma_{E+})^2 + N(\sigma_{E-})^2 + N(\sigma_{Pp})^2}$$

- Mix Events
  $\rightarrow$ Pair particle from Event $i$ with particle from Event $j$
  $\rightarrow$ Z-vertex, two charge and minimum energy cuts

- Scale Mixed Events
  Scalefactor = Data Area/Mixed Area
Radiative Corrections [In Progress]

- **Standard treatment** [known beam energy]:
  - Type I: e-p scattering with the electron detected
  - Type II: e-p scattering with the proton detected
  - Calculate $\sigma_{RC}/\sigma_B$

- **CLAS TPE treatment**
  - Type III: e-p scattering bremsstrahlung with the electron and proton detected
  - Not trivial due to our cuts non monochromatic beam.
  - Resolution: Simulate & integrate
  - ELRADGEN (hep-ph/088106)
**Projections**

- **CLAS** will map out the TPE effect over large areas of $Q^2$ and $\epsilon$
- Not the only game in town: **Olympus at DESY** and **VEP-III at Novosibirsk**
- **CLAS** experiment will be able to obtain $< 1\%$ statistical and systematic uncertainties out to $Q^2 = 2\text{GeV}^2$
Summary

- TPE Analysis uses non-standard PID & event selection
  → Exploit over constrained kinematics
- Working on simulations for detector holes & acceptance
- Trying several background subtraction methods for low $\varepsilon$ events
- Special care in radiative corrections due to Non-standard experimental setup and elastic cuts
- Expect first results this fall
Thank you
Thank you
$\Delta E - \varepsilon$ Dependence

\begin{align*}
\varepsilon &= 0.10 - 0.50 \\
\varepsilon &= 0.50 - 0.70 \\
\varepsilon &= 0.70 - 0.80 \\
\varepsilon &= 0.80 - 0.90 \\
\varepsilon &= 0.90 - 0.95 \\
\varepsilon &= 0.95 - 1.00
\end{align*}
$\Delta E +: \varepsilon$ Dependence

![Graphs showing the dependence of $\varepsilon$ on $\Delta E$ with different energy ranges.](image-url)
$\Delta P_p : \varepsilon$ Dependence

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Personnel

1. **Spokes Persons**
   - Larry Weinstein, Brian Raue, Will Brooks, John Arrington, Andrei Afanasev & Kyungseon Joo

2. **Post Docs**
   - Puneet Khetarpal
   - Mauri Ungaro
   - Robert Bennett

3. **Graduate Students**
   - Dasuni Adikaram
   - Dipak Rimal
   - Cristian Peña
   - Hashir Rashad