Modeling Radiative Processes for the OLYMPUS Experiment

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CFNS Ad-Hoc Meeting on Radiative Corrections

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Polarized and unpolarized measurements of $\mu G_E/G_M$ disagree.
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Hard TPE would cause asymmetry between $e^+p$ and $e^-p$ cross sections.

\[ M = \begin{align*} &\begin{array}{c} \text{Diagram 1} \\ + \\
\end{array} + \mathcal{O}(\alpha^3) \end{align*} \]
Hard TPE would cause asymmetry between $e^+p$ and $e^-p$ cross sections.

\[ M = \begin{pmatrix} \begin{array}{cc} \text{Diagram 1} & + \\ \text{Diagram 2} & + O(\alpha^3) \end{array} \end{pmatrix} \]

\[
\sigma \approx |M|^2 = \begin{pmatrix} \begin{array}{cc} \text{Diagram 3} & \pm 2\text{Re} \end{array} \end{pmatrix}^2 + O(\alpha^4)
\]
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$$\mathcal{M} = 2\Re \{ M_1 \gamma M_2 \gamma \} + \mathcal{O}(\alpha^3)$$

$$\sigma \approx |\mathcal{M}|^2 = \pm 2\Re \left[ \mathcal{M}_1 \gamma \mathcal{M}_2 \gamma \right] + \mathcal{O}(\alpha^4)$$

$$\frac{\sigma_{e^+ p}}{\sigma_{e^- p}} \approx 1 + \frac{4\Re \{ \mathcal{M}_2 \gamma \mathcal{M}_1 \gamma \}}{|\mathcal{M}_1 \gamma|^2}$$
Other higher-order processes also contribute.

Soft TPE

e-vertex correction

$p$-vertex correction

Vacuum polarization
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Vacuum polarization

Soft Bremsstrahlung
Charge-odd radiative corrections

Soft two-photon exchange

Bremsstrahlung interference
In my talk today:

- Review of the OLYMPUS Results
- Radiative Corrections in OLYMPUS
- New Charge-Averaged Cross Section Analysis
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- Radiative Corrections in OLYMPUS
- New Charge-Averaged Cross Section Analysis
Predictions for 2 GeV Beam

\[ \frac{\sigma_{e^+p}}{\sigma_{e^-p}} \] for a 2 GeV beam

\[ Q^2 [\text{GeV}/c]^2 \]
Predictions for 2 GeV Beam

$Q^2 [\text{GeV}/c]^2$ for a 2 GeV beam

- Blunden $N$ only
- Blunden $N + \Delta$
- Afanasev (GPDs)

$\frac{\sigma_{e^+p}}{\sigma_{e^-p}}$ vs. $\epsilon$
Predictions for 2 GeV Beam

\[ \frac{\sigma_{e^+p}}{\sigma_{e^-p}} \] vs. \[ \epsilon \]

\[ Q^2 \ [\text{GeV/c}]^2 \] for a 2 GeV beam

- Blunden \( N \) only
- Blunden \( N + \Delta \)
- Afanasev (GPDs)
- Bernauer
1960s data lack the coverage and precision to make strong claims about TPE.
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OLYMPUS was one of three new experiments to measure the $e^+ p / e^- p$ cross section ratio.
The OLYMPUS Experiment at DESY

- Alternating 2 GeV $e^+$ and $e^-$ stored beams
- Window-less hydrogen target
- Former BLAST Spectrometer
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[Diagram showing the setup of Drift chambers, ToFs, and the e+ beam hitting the target with proton trajectories indicated.]
OLYMPUS Results

\[ Q^2 \ [\text{GeV/c}^2] \text{ for a 2 GeV beam} \]

- Blunden $N$ only
- Blunden $N + \Delta$
- Afanasev (GPDs)
- Bernauer
- OLYMPUS data

Henderson et al., PRL 118 092501 (2017)
The three experiments are consistent and slightly below Blunden.

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Forward calorimeters were designed to monitor the symmetric Møller/Bhabha rate.
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The luminosity normalization method in OLYMPUS was highly robust.

\[ \mathcal{L} = \frac{N_{\text{multi}} \times N_{\text{bunches}}}{N_{\text{Møller}} \times \sigma_{ep}} + \ldots \text{corrections} \]

Method is immune to:
- Simulation error
- Inefficiency
- Beam alignment

NIM A 877 p. 112 (2018)
How do the OLYMPUS results compare with the size of the discrepancy?

Assumptions about hard TPE:

- Preserves the linearity (in $\epsilon$) of reduced cross section.
- Has negligible impact on polarization transfer measurements.
- Zero as $\epsilon \to 1$. 
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Inputs:

- Global fits to $G_E$ and $G_M$ (unpolarized).
- Assume true $\mu G_E/G_M = 1 - 0.12Q^2$ (polarized)
OLYMPUS data match the size of the discrepancy, assuming Bernauer FFs.

\[ E_{\text{beam}} = 2.01 \text{ GeV} \]

\[ R_{2\gamma} \]

\[ \epsilon \]

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The "standard" approach to radiative corrections:

\[
\frac{d\sigma}{d\Omega_{\text{meas.}}} = \frac{d\sigma}{d\Omega_{\text{Born}}} \times [1 + \delta(\Delta E)]
\]

- Inclusive measurement
  - Soft bremsstrahlung defined by \(e^- \Delta E\)
- Good resolution
  - Small \(\Delta E\), set by detector resolution
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- **Inclusive measurement**
  - Soft bremsstrahlung defined by \(e^- \Delta E\)

- **Good resolution**
  - Small \(\Delta E\), set by detector resolution

![Graph showing inclusive measurement and good resolution](image)
Mo-Tsai and Maximon-Tjon prescriptions have different definitions of soft TPE.
OLYMPUS had special RC needs.

- Coincidence Measurement
  - Soft bremsstrahlung defined by non-trivial exclusivity cuts on both $e^\pm$ and $p$.
- Not-so-great momentum resolution
  - Deep-tail contributions
  - Soft-photon approximations are bad!

$\rightarrow$ Adopt peaking-approx. MC approach like that developed for NE18
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- Coincidence Measurement
  - Soft bremsstrahlung defined by non-trivial exclusivity cuts on both $e^\pm$ and $p$.
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→ Adopt peaking-approx. MC approach like that developed for NE18

- Bremsstrahlung interference is a charge-odd correction!
  - Peaking approximations that fail to treat interferences are bad!

→ write a custom MC event generator!
The OLYMPUS generator used two approaches.

1 Conventional $\mathcal{O}(\alpha^3)$ approach
   - Distinguish between near-elastic and tail.
   - near elastic: $\frac{d\sigma}{d\Omega}_{\text{meas.}} = \frac{d\sigma}{d\Omega}_{\text{Born}} \times [1 + \delta(\Delta E)]$
   - tail: tree-level bremsstrahlung cross section
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   - near elastic: \[ \frac{d\sigma}{d\Omega}_{\text{meas.}} = \frac{d\sigma}{d\Omega}_{\text{Born}} \times [1 + \delta(\Delta E)] \]
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2. Exponentiated approach
   - Based on prev. work by J. M. Friedrich, J. C. Bernauer at Mainz A1
Exponentiated Approach

Assumptions:

- Multi-photon kinematics can be well-approximated by single-photon bremsstrahlung kinematics
- Differential cross section takes an exponentiated form:

\[ d^5 \sigma = \frac{d\sigma}{d\Omega_{\text{Born}}} e^\delta (\partial_{\vec{p}_\gamma} \delta) \]

- The differential part of \( \delta \) is well-approximated

\[ \partial_{\vec{p}_\gamma} \delta \rightarrow \frac{d^5 \sigma}{d\Omega_e d\Omega_\gamma E_{\gamma\text{Brems.}}} / \frac{d\sigma}{d\Omega_{\text{Born}}} \]

- \( \delta \) given by standard prescription (e.g. Mo-Tsai)

\[ d^5 \sigma = \frac{d^5 \sigma}{d\Omega_e d\Omega_\gamma E_{\gamma\text{Brems.}}} e^{\delta(E_{\gamma})} \]
Exponentiated approach matches standard correction at low $E_\gamma$. 

[Graph with legends and axes labels]
Exponentiated approach matches standard correction at low $E_\gamma$. 

![Graph showing the exponentiated approach matches standard correction at low $E_\gamma$.]
Sampling kinematics in MC generator is non-trivial.

See:
- J. C. Bernauer thesis, section 5.2
The OLYMPUS radiative correction is significantly larger than the hard TPE effect.
What can be improved

- I need to document and publish.
- Use off-shell proton currents for calculating diagrams
- Add models of hard TPE
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In progress: charge-averaged cross sections

Effects of hard TPE cancel!

\[
\left\langle \frac{d\sigma}{d\Omega} \right\rangle \equiv \frac{1}{2} \left[ \frac{d\sigma}{d\Omega_{e^+p}} + \frac{d\sigma}{d\Omega_{e^-p}} \right]
\]
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Challenges:

- Absolute efficiency
- Absolute track reconstruction efficiency
- Absolute luminosity
Absolute efficiency was studied by tracking while ignoring tracking planes.
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Absolute efficiency was studied by tracking while ignoring tracking planes. Draw against these maps to determine which hits (if any from the track) would be passed from that cell layer to the reconstruction of simulation. Separate sets of maps were constructed for position and electron beam operation since the noise conditions in the innermost layers differed significantly enough to induce an efficiency difference. An example set of maps for an outer layer, where the efficiency was quite uniform and high, is shown in Figure 6-2.

Figure 6-2: Probability maps for the eight possible combinations of hits in the outermost left cell layer during e+p running, where x is the distance from the first wire and is the track azimuthal angle. The three layers are labeled 0, 1, and 2, and the plot titles indicate which wires are hit in a given map. Note that the dominant probability is for all three wires to fire, outside of the region of a known disconnected cell at x ≈ 1400 mm. Additionally, lower single wire efficiencies occur at two other locations but do not cause a significant correlated probability of missing all three hits in the cell layer.
Track reconstruction was studied using single-arm event selection.

![Graph showing efficiency for different types of leptons as a function of lepton angle. The graph includes lines for $e^-$, $e^-$ subtr., $e^+$, and $e^+$ subtr., with data points at various angles.]
OLYMPUS was not designed with absolute luminosity in mind.

1 Beam current $\times$ Target Density

- Target density combines gas flow (?), target conductance, temperature-dependence
- We know these are uncertain, but by how much?
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1. Beam current × Target Density
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2. Forward tracking telescopes
   - Magnetic field makes absolute acceptance tricky
   - Systematics in *addition* to those of main spectrometer
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1 Beam current $\times$ Target Density
   - Target density combines gas flow (?), target conductance, temperature-dependence
   - We know these are uncertain, but by how much?

2 Forward tracking telescopes
   - Magnetic field makes absolute acceptance tricky
   - Systematics in *addition* to those of main spectrometer

3 Multi-interaction effects in forward calorimeters
   - Extremely sensitive to beam position, alignment
   - Effect can be estimated: 7% normalization uncertainty
Charge-averaged cross section

\[ \frac{\sigma_{e^+} + \sigma_{e^-}}{\sigma_{\text{dipole}}} \]

\[ Q^2 \ [\text{GeV}^2/\text{c}^2] \]

Bernauer
Kelly
Arrington 03
Arrington 07
OLYMPUS
The charge-odd radiative correction is a significant fraction of the total.
To Recap:

- OLYMPUS measured small hard TPE effect for $Q^2 < 2$. 

.png
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- OLYMPUS measured small hard TPE effect for $Q^2 < 2$.
- Custom event generator considered
  - Mo-Tsai and Maximon-Tjon soft TPE
  - Exponentiated and $\alpha^3$
- Charge-averaged cross section eliminates TPE effects.
Hoping for interesting new data!

Positron Working Group at Jefferson Lab