Two-photon exchange in lepton-proton elastic scattering

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Cross section and form factors for elastic lepton-proton scattering

The cross section:

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

with:

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

Fourier-transform of \( G_E, G_M \) → spatial distribution (Breit frame)

\[
\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0} \quad \langle r_M^2 \rangle = -6\hbar^2 \left. \frac{d(G_M/\mu_p)}{dQ^2} \right|_{Q^2=0}
\]
History of unpolarized electron-proton scattering

![Graph showing the history of unpolarized electron-proton scattering with data points for different years and authors. The x-axis represents the year from 1965 to 2010, and the y-axis represents the squared momentum transfer ($Q^2$) in (GeV/c)^2. The graph includes data from various authors: Andivahis, Bartel, Berger, Bernauer, Borkowski, Bosted, Christy, Goitein, Janssens, Litt, Price, Qattan, Rock, Sill, Simon, Stein, and Walker.]
Measurements with polarization: FF ratio

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

Year
unpolarized
Crawford
Dieterich
Gayou
Jones
MacLachlan
Meziane
Milbrath
Pospischil
Puckett
Punjabi
Ron
Zhan
Rosenbluth Polarization
Most likely explanation: Two Photon Exchange
Most likely explanation: Two Photon Exchange

$2 \Rightarrow (+) + (+)$
Most likely explanation: Two Photon Exchange

Impact of direct measurement

- Reconcile Rosenbluth and polarized data?
- How to treat (off-shell) hadron line?
Most likely explanation: Two Photon Exchange

Impact of direct measurement
- Reconcile Rosenbluth and polarized data?
- How to treat (off-shell) hadron line?

Method
- Mixed term changes sign with lepton sign
- Measure ratio of positron-proton to electron-proton scattering
Direct measurement: Three modern experiments

**VEPP-3**
- 1.6/1 GeV beam
- no field
- PRL 114, 062005

**CLAS**
- $e^{-}$ to $\gamma$ to $e^{+/-}$ -beam
- PRL 114, 062003

**OLYMPUS**
- DORIS @ DESY
- 2 GeV beam
- under analysis

![Graph showing kinematic reach of two-photon experiments](image-url)
VEPP-3 results (I. A. Rachek et al., Phys. Rev. Lett 114, 062005)
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\[ R_{2\gamma} \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \chi^2 )</th>
<th>d.f.</th>
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No hard TPE ($R_{2\gamma} \equiv 1$)

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Fit to world data set:

- 12 non-overlapping points from CLAS
- 4 Vepp-3 points

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Definitive answer still out!

- Important to distinguish models:
  - higher $Q^2$
  - absolute normalization
  - more points, better statistics

- OLYMPUS designed to have all of this!

Fit to world data set:

- 12 non-overlapping points
- χ²/νd.f.:
  - Z & Y (N): 1.09
  - Z & Y (N+∆): 1.03
  - Blunden (N): 1.06
  - No TPE: 2.10
  - Point-proton: 6.96
  - Mainz: 0.666

Definitive answer still out!
The OLYMPUS collaboration

- Arizona State University, USA
- DESY, Hamburg, Germany
- Hampton University, USA
- INFN, Bari, Italy
- INFN, Ferrara, Italy
- INFN, Rome, Italy
- MIT Laboratory for Nuclear Science, Cambridge, USA
- Petersburg Nuclear Physics Institute, Gatchina, Russia
- University of Bonn, Bonn, Germany
- University of Glasgow, United Kingdom
- University of Mainz, Mainz, Germany
- University of New Hampshire, USA
- Yerevan Physics Institute, Armenia

Analysis effort carried by students:
- Lauren Ice (ASU)
- Dmitry Khaneft (Mainz)
- Colton O'Connor (MIT)
- Brian Henderson (MIT)
- Rebecca Russell (MIT)
- Axel Schmidt (MIT)
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At DESY: DORIS
Anatomy of the OLYMPUS detector

- Target chamber with target cell

Beam direction

R. Milner et al., NIMA 741 (2014) 1-17
Anatomy of the OLYMPUS detector

- Target chamber with target cell
- Toroid magnet coils

R. Milner et al., NIMA 741 (2014) 1-17
Anatomy of the OLYMPUS detector

- Target chamber with target cell
- Toroid magnet coils (half shown)

R. Milner et al., NIMA 741 (2014) 1-17
Anatomy of the OLYMPUS detector

- Target chamber with target cell
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R. Milner et al., NIMA 741 (2014) 1-17
Anatomy of the OLYMPUS detector

- Target chamber with target cell
- Toroid magnet coils (half shown)
- Drift chambers
- Time of flight scintillators

R. Milner et al., NIMA 741 (2014) 1-17
Anatomy of the OLYMPUS detector

- Target chamber with target cell
- Toroid magnet coils (half shown)
- Drift chambers
- Time of flight scintillators
- Dual luminosity monitors
  - 12°-detector
  - Symmetric Møller/Bhabha

R. Milner et al., NIMA 741 (2014) 1-17
Total data taken

- Electron, positive toroid: $1.93 \text{ fb}^{-1}$
- Positron, positive toroid: $1.96 \text{ fb}^{-1}$
- Electron, negative toroid: $0.24 \text{ fb}^{-1}$
- Positron, negative toroid: $0.32 \text{ fb}^{-1}$
- Total: $4.45 \text{ fb}^{-1}$

> $4 \text{ fb}^{-1}$ data taken
Selected $3.2 \text{ fb}^{-1}$ high quality subset
“Straight forward” analysis

- Measure data
- Model experiment in simulation
- Generate pseudo data
- Track data + pseudo data
- Define cuts
- Background subtraction
- Build ratio

\[ r_{e^+_{e^-}} = \frac{N_{e^+_{exp}}}{N_{e^-_{exp}}} \times \frac{N_{e^-_{MC}}}{N_{e^+_{MC}}} \]
The crux: systematics

- Measure data
- Model experiment in simulation
- Generate pseudo data
- Track data + pseudo data
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\[ r_{e^+ / e^-} = \frac{N_{e^+}^{exp}}{N_{e^-}^{exp}} \times \frac{N_{e^-}^{MC}}{N_{e^+}^{MC}} \]
The crux: systematics

- Measure data \textit{Lumi. asymmetry? Time stability?}
- Model experiment in simulation
- Generate pseudo data
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\[ r_{e^+/e^-} = \frac{N_{e^+}^{\text{exp}}}{N_{e^-}^{\text{exp}}} \times \frac{N_{e^-}^{\text{MC}}}{N_{e^+}^{\text{MC}}} \]
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- Measure data Lumi. asymmetry? Time stability?
- Model experiment in simulation Reality matched?
- Generate pseudo data Radiative corrections? F.F.?
- Track data + pseudo data
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- Measure data Lumi. asymmetry? Time stability?
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- Track data + pseudo data Tracker efficiency?
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\[ r_{e^+/e^-} = \frac{N_{e^+}^{\text{exp}}}{N_{e^-}^{\text{exp}}} \times \frac{N_{e^-}^{\text{MC}}}{N_{e^+}^{\text{MC}}} \]
The crux: systematics

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- Define cuts Cut bias?
- Background subtraction Background model?
- Build ratio

\[
r_{e^+e^-} = \frac{N_{e^+}^{\text{exp}}}{N_{e^-}^{\text{exp}}} \times \frac{N_{e^-}^{\text{MC}}}{N_{e^+}^{\text{MC}}} \]

How to check systematics

- Redundancy
  - Multiple luminosity monitors
  - Multiple MC generators
  - Multiple trackers
  - Multiple analyses

- Associated quantities
  - Lepton left vs. lepton right by species
  - Charge average: $\frac{\sigma_{e^+}^{\text{exp}} + \sigma_{e^-}^{\text{exp}}}{\sigma_{e^+}^{\text{MC}} + \sigma_{e^-}^{\text{MC}}} \approx 1$
    $\Rightarrow$ TPE cancels in first order
### The crux: systematics

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<td>Bkgd. subtr.</td>
<td></td>
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Baseline: Dipole F. F., Maximon Tjon rad. corrections

Shift in ratio $Q^2$ [(GeV/c)$^2$]

- Mainz F. F. fit
- Kelly F. F. fit
- Soft photon approx.
- Meister Yennie
- Mo Tsai
- No exponentiation
### The crux: systematics

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Luminosity measurements

Redundant systems:

- Slow control luminosity
  - beam current, target flow, temperature
- Symmetric Møller/Bhabha monitor
  - MC of both processes
- $e^\pm e^- + e^\pm p$ double coincidence in symmetric Møller/Bhabha detector
- $12^\circ$ monitor
  - two independent $e^\pm p$ measurements
Symmetric Møller/Bhabha monitor

1 GeV/3 GeV
$e^\pm + e^- \&\& e^\pm + p$
$e^\pm e^- + e^\pm p$ double coincidence

- Calculate coincidence rate from $e^\pm p$ simulation and $e^\pm e^-$ rate measurement
- Correct for luminosity variance (time / bunch charge)
- Result is independent of:
  - detector efficiency
  - Møller / Bhabha cross section
- Reduced sensitivity on beam position, geometry
Slow control luminosity induced asymmetry: $\sim 0.55\%$

Uncertainty: 0.10\% stat. 0.31\% syst.

$\langle \varepsilon \rangle = 0.99975$, $\langle Q^2 \rangle = 0.002 \text{ (GeV/c)}^2$
Yields using SM double coinc. luminosity

Left and right agrees to within 0.1%

TPE at $Q^2 = 0.168 \text{(GeV/c)}^2$?

Uncertainty: 0.04% stat., < 0.5% syst.

Analysis by Brian Henderson
The crux: systematics

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Lepton left vs. lepton right

-20%  -15%  -10%  -5%  0%  5%  10%  15%  20%

Raw yield, no Monte Carlo
Tests “flatness”
OLYMPUS: good statistics @ many slices
Charge average

\[ Q^2 \] \text{[(GeV/c)^2]}
Charge average

![Graph showing spread in charge average against Q^2.](image)
$G_{M}/(\mu_{p} G_{\text{std.dipole}})$

$Q^2 [(\text{GeV}/c)^2]$
The crux: systematics

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Yields

\[
\begin{align*}
\text{Cross section } [\text{nbc}^2/\text{GeV}^2] \\
Q^2 [\text{GeV}/c]^2
\end{align*}
\]

PRELIMINARY

Analysis by Axel Schmidt
Conclusion

- Form factor discrepancy: TPE probable candidate
- Three modern experiments
- Results (CLAS, VEPP-3) so far (my view):
  - theory roughly correct size
  - but wrong functional form
- OLYMPUS is on its way to give definitive result
  - more data points
  - better statistics
  - many systematics tests
- Bonus physics: Structure in $G_M$
OLYMPUS: Projected performance

2 GeV beam, $Q^2$-range: 0.6 to 2.2 (GeV/c)$^2$
Cuts (slice at $Q^2 = 1.175 \text{(GeV/c)}^2$)

Cut on Target + PID
+ time at vertex
+ rec. beam energy
+ vertex correlation