Hall A DVCS Program

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JLab Pizza Seminar, 2/25/2105
Outline

• DVCS Reaction
• Cross section and GPD dependence
• Simulation
• Experimental setup
• 2010 and 2014 runs
Reaction $ep \rightarrow epy$

Belitsky, Müller, Kirchner
Reaction $ep \rightarrow epy$

- 5 relevant variables:
  - $Q^2$, $x_{Bj}$, $t = \Delta^2$, $\phi_{\gamma\gamma}$, $\phi_e$

\[ x_{Bj} = \frac{Q^2}{2p_\mu \cdot q^\mu} \]

\[ \Delta = (q - q') = (p' - p) \]
Bethe-Heitler and VCS

\[ ep \rightarrow ep\gamma \]

\[ p' = p + \Delta \]
Bethe-Heitler and VCS

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Bethe-Heitler (BH)
Bethe-Heitler and VCS

\[ ep \rightarrow ep\gamma \]

\[ p' = p + \Delta \]

\( e^- \quad e^-' \quad q' \quad \Delta \quad q = q' + \Delta \quad q' \)

Bethe-Heitler (BH)

Virtual Compton Scattering (VCS)
QCD Limit of VCS

$Q^2 \rightarrow \text{large}$

Deeply Virtual Compton Scattering (DVCS)
$ep \rightarrow e\gamma$ cross section and Elastic Form Factors

- Total $ep \rightarrow e\gamma$ cross section

$$d^4\sigma = |BH + DVCS|^2$$
$ep \rightarrow e p \gamma$ cross section and Elastic Form Factors

- Total $ep \rightarrow e p \gamma$ cross section

$$d^4 \sigma = |BH + DVCS|^2$$

- Bethe-Heitler dependence on Dirac and Pauli Form Factors $(F_1, F_2)$ well-known

$$BH \equiv BH \left( F_1, F_2 \right)$$
$ep \rightarrow epy$ cross section and Elastic Form Factors

- Total $ep \rightarrow epy$ cross section

$$d^4\sigma = |BH + DVCS|^2$$

- Bethe-Heitler dependence on Dirac and Pauli Form Factors ($F_1, F_2$) well-known

$$BH \equiv BH (F_1, F_2)$$

- $F_1$ and $F_2$ describe 2D spatial distribution of charge and magnetization of nucleon after integration over longitudinal space coordinates
Compton Form Factors (CFFs) and Generalized Parton Distributions (GPDs)

- GPDs describe the transverse spatial distribution of quarks as a function of longitudinal momentum fraction $x \pm \xi$

$$P = \frac{p + p'}{2}$$

$$\xi = \frac{-(q + q')^2}{2(q + q') \cdot P} = \frac{x_B}{2 - x_B}$$

Quark Loop

GPDs
Compton Form Factors (CFFs) and Generalized Parton Distributions (GPDs)

- GPDs describe the transverse spatial distribution of quarks as a function of longitudinal momentum fraction $x \pm \xi$

$$P = \frac{p + p'}{2}$$

$$\xi = \frac{-(q + q')^2}{2(q + q') \cdot P} \quad -t < Q^2 < 0 \quad \frac{x_B}{2 - x_B}$$

- DVCS amplitude depends directly on CFFs ($H, E, \ldots$) which are integrals of GPDs ($H, \tilde{H}, E, \tilde{E}$)

$$DVCS \equiv DVCS \left( H, \tilde{H}, E, \tilde{E} \right)$$

Quark Loop
Compton Form Factors (CFFs) and Generalized Parton Distributions (GPDs)

• Belitsky, Müller, and Kirchner’s definitions of CFFs
  o Similar definitions for higher twist terms

\[
\{ \mathcal{H}, \mathcal{E} \} = \int_{-1}^{1} dx \frac{\{ H, E \}(x, -\xi, t)}{x \pm \xi}
\]

\[
\{ \tilde{\mathcal{H}}, \tilde{\mathcal{E}} \} = \int_{-1}^{1} dx \frac{\{ \tilde{H}, \tilde{E} \}(x, -\xi, t)}{x \pm \xi}
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\]

Integrate because of loop in diagram
GPDs, the Ji Sum Rule and the Proton Spin Puzzle

- $J_q$ is the total angular momentum contribution from quarks and anti-quarks of flavor $q$ in the nucleon
  - Involves integrals of $H_q$ and $E_q$ in the limit that $t \to 0$

$$J_q = \frac{1}{2} \int_{-1}^{1} dxxx \left[ H_q (x, 0, 0) + E_q (x, 0, 0) \right]$$

$$S_p = \frac{1}{2} = \sum_q J_q + J_g$$
Total Cross Section

\[ d^4 \sigma = |BH|^2 + |DVCS|^2 + I (BH \cdot DVCS) \]
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Significant deviation from Bethe-Heitler. Both Interference and \(|DVCS|^2\) contribute.

Results from E00-110
C. Munoz-Camacho et. al.
PRL 97, 262002 (2006)
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\[ d^4 \sigma = |BH|^2 + |DVCS|^2 + I (BH \cdot DVCS) \]

Known

Well described by leading-twist contribution

\[ (d^4 \sigma^+ - d^4 \sigma^-)/2 \rightarrow Im(BH^*DVCS) \alpha \sin(\phi_{\gamma \gamma}) \]

\[ (d^4 \sigma^+ + d^4 \sigma^-)/2 \rightarrow Re(BH^*DVCS) \alpha \cos(\phi_{\gamma \gamma}) \]

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**Total Cross Section**

\[
\frac{d^4 \sigma}{d^4 \sigma} = |BH|^2 + |DVCS|^2 + I (BH \cdot DVCS)
\]

- Measured
- Known

\[
\frac{(d^4 \sigma^+ - d^4 \sigma^-)}{2} \rightarrow \text{Im}(BH \cdot DVCS) \propto \sin(\gamma \gamma)
\]

\[
\frac{(d^4 \sigma^+ + d^4 \sigma^-)}{2} \rightarrow \text{Re}(BH \cdot DVCS) \propto \cos(\gamma \gamma)
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Total Cross Section

\[ d^4\sigma = |BH|^2 + |DVCS|^2 + I(BH \cdot DVCS) \]

Measured

Known

Fit with Data

Well described by leading-twist contribution

\[
(d^4\sigma^+ - d^4\sigma^-)/2 \rightarrow \text{Im}(BH*DVCS) \propto \sin(\phi_{\gamma\gamma})
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(d^4\sigma^+ + d^4\sigma^-)/2 \rightarrow \text{Re}(BH*DVCS) \propto \cos(\phi_{\gamma\gamma})
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Proposed Kinematics

• Measuring at 3 fixed values of $x_{Bj}$ and varying $Q^2$ for high precision measurement DVCS cross section dependence
  o Study possible influence of higher-order diagrams suppressed by powers of $1/Q^2$

• Want to utilize higher beam energy to explore higher $Q^2$ and $x_{Bj}$ region
Proposed Kinematics

![Graph showing DVCS measurements in Hall A/JLab](image)
Proposed Kinematics

DVCS measurements In Hall A/JLab

$Q^2 (GeV^2)$

$W^2 < 4 GeV^2$

Unphysical with $E_{beam} \leq 11$ GeV

$E_{beam} = 6.6$ GeV

$E_{beam} = 8.8$ GeV

$E_{beam} = 11.0$ GeV

$E_{beam} = 5.75$ GeV

$X_{Bj}$
Monte Carlo Simulation

• Based on Geant4 simulation written by Carlos Munoz Camacho and Rafayel Paremuzyan
  o Simulation of interactions inside calorimeter not included

• CFF model taken from Kroll et. al.

• Total cross section (DVCS+BH) computed analytically using produced CFFs given initial kinematic settings
  o Beam energy
  o Calorimeter and HRS positions
  o HRS momentum acceptance

• Focused on count rate and cross section evaluation for future run plans
Monte Carlo Simulation

• Set target parameters, detector geometries, and detector acceptances

• Generate initial vertex and initial Bremsstrahlung

• Generate uniformly in phase space $x_{Bj}, Q^2, \varphi_e, t,$ and $\phi_{\gamma\gamma}$
  o Reject unphysical points
  o Phase Space Factor (PSF) = $\Delta x_{Bj} \Delta Q^2 \Delta t \Delta \phi_{\gamma\gamma}$

• Use generated kinematics along with model values of CFFs to calculate cross section
Monte Carlo Integration

- Integrate over experimental bin\#n to find expected yield

\[ L = \frac{X \rho I}{e} \frac{N_0}{A} \]

\[ PSF = \Delta x B_j \Delta Q^2 \Delta t \Delta \phi_{\gamma \gamma} \]

\[ Y(n) = \frac{L \cdot T}{N_{MC}} \sum_{\text{event } i} d^4 \sigma_i \cdot PSF_i \cdot \chi_n (t_{\min,i} - t_i) \]

- \( \chi_n \) = Cut on bin\#n in \( t \) increments of 0.1 GeV\(^2\)
Results – Count Yield

Projected Counts for $E_b = 9.60$ GeV
1 day(s) running at $l_b = 13.73$ μ, $A, x_{Bj} = 0.36, Q^2 = 4.50$

Helicity Sum
Helicity Diff
Bethe Heitler
Projected Counts for $E_b = 9.60$ GeV
4 day(s) running at $l_b = 13.73 \mu A$, $x_{Bj} = 0.50$, $Q^2 = 5.80$

Results – Count Yield

yield

Helicity Sum
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Results – Count Yield

Projected Counts for $E_b = 9.60$ GeV

20 day(s) running at $I_b = 19.77 \mu A$, $x_{Bj} = 0.60$, $Q^2 = 9.00$

Helicity Sum

Helicity Diff

Bethe Heitler

Projected Counts for $E_b = 9.60$ GeV

20 day(s) running at $I_b = 19.77 \mu A$, $x_{Bj} = 0.60$, $Q^2 = 9.00$
Results – Cross Section

\[ E_p = 9.60 \text{ GeV}, \quad x_B = 0.50, \quad Q^2 = 5.80 \]

\[ \frac{d^4\sigma}{dx_B dq^2 dt d\phi_{\gamma \gamma}} \]

- Helicity Sum
- Helicity Diff
- Bethe Heitler
Experimental Setup

- LH$_2$ Target
- 13 x16 PbF$_2$ EM calorimeter
  - Tags emitted photon
  - 3 x 3 x 18 cm$^3$
  - $\rho = 7.77$ g/cm$^3$
  - $X_0 = 0.93$ cm
  - Cerenkov only
- Left HRS
  - Tags scattered electron
Experimental Setup
E07-007: Rosenbluth-like separation of DVCS

Electron acceptance checks using DIS data
Working on final global normalizations (multi-tracks, dead-time, radiative corrections)

DIS cross-section vs run number

\[ \pm 5\% \text{ around expected DIS c.s.} \]

M. Defurne, CEA Saclay

Data taken in late 2010
Preliminary results expected in 2-3 months

3 kinematic points:
\[ x_B=0.36, Q^2=1.5, 1.75, 2.0 \text{ GeV}^2 \]
5 bins in \( t \)
2 beam energies per point

\[ ep \rightarrow e\gamma X \] missing mass squared

Analysis underway (A. Marti, IPNO & Valencia U)
E08-025: DVCS on the neutron

- Beam energy separation off the neutron using an LD2 target
- Important contribution of $|DVCS|^2$ term expected in unpolarized cross section

Data taken in Fall 2010 concurrently with E07-007

Analysis ongoing:
- Calibrations completed
- Exclusive data isolated
- Cross section extraction underway

$Q^2=1.75 \text{ GeV}^2$, $x_B=0.36$

$eN \rightarrow e \gamma X$

![Graph showing Missing Mass Squared (LD2-LH2)](image)
E12-06-114: Fall 2014 Run

Beam line commissioning:
- Moller measurement (88% polarization)
- BPM calibration (+ harps operational)
- BCM calibration
- New raster commissioning

DVCS experiment commissioning:
- Coincidence (e + g) trigger
- 1 GHz sampling electronics
- ep → ep calorimeter elastic calibration
- (Almost) completed the 1st DVCS kinematic setting

\[ \pi^0 \text{'s reconstructed in DVCS calorimeter} \]

\[ e p \rightarrow e \gamma X \text{ missing mass squared} \]
Summary

• Measuring total $ep \rightarrow ep \gamma$ cross section over full 12 GeV range in $x_{Bj}$, $Q^2$, $t$, $\phi_{\gamma\gamma}$ allows us to isolate GPD terms from DVCS amplitude.

• GPD variation with $t \rightarrow$ Traverse spatial distributions of quarks.

• GPD variation with $x_{Bj} \rightarrow$ Longitudinal momentum distribution of quarks.

• A better understanding of GPDs leads to a better understanding of the inner structure of the proton and the distribution of quarks within it.
  o Can also lead to a better understanding of (and possible resolution to) the proton spin puzzle.
E12-06-114: DVCS at 11 GeV

Scaling tests of the DVCS cross section

- High impact experiment for nucleon 3D imaging program
- High precision $Q^2$ dependence of the DVCS cross section at constant $x_{Bj}$.
- CEBAF12 will allow to explore for the first time the high $x_{Bj}$ region.

Total = 100 days (88+12 days calibration) approved