E12-06-114: Deeply Virtual Compton Scattering at Jefferson Lab, Hall A

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Outline

• Introduction – physics motivations
• DVCS at Jlab, Hall A – Goal
• Experimental setup
• Overview of the ongoing data analysis
• Summary and Outlook
Generalized Parton Distributions (GPDs)

- Elastic Scattering (ep → e’p’) ➤ Elastic Form Factors ➤ Spatial distribution
- Inelastic Scattering (ep → e’X) ➤ Parton Distribution Functions ➤ Momentum distribution
- DVCS (ep → e’p’γ) ➤ Generalized Parton Distributions ➤ Spatial-Momentum correlations & Spin structure
Deeply Virtual Compton Scattering (DVCS)

In the Bjorken Limit: \( Q^2 = \frac{-q^2}{\nu} \rightarrow \infty \) \( x_B = \frac{Q^2}{2M\nu} \) fixed

Hard part
(QED, can be computed)

Soft part
Parametrized by GPDs

Proton structure described by 4 quark GPDs:
\( H, E, \tilde{H}, \tilde{E} \)

\( t = (p' - p)^2 \)
\( \xi \approx \frac{x_B}{2 - x_B} \)

DVCS cross section \( \rightarrow \) GPDs \( \rightarrow \) Description of the proton internal structure.
DVCS and Bethe-Heitler

At leading twist:

\[ d^5 \sigma \rightarrow d^5 \sigma = \Im m (T^{BH} \cdot T^{DVCS}) \]

\[ d^5 \sigma + d^5 \sigma = |BH|^2 + \Re e (T^{BH} \cdot T^{DVCS}) + |DVCS|^2 \]

Known to 1%
DVCS at Jefferson Lab, Hall A – Goal

- Data acquisition between Fall 2014 and Fall 2016

### E12-06-114 goals:
- Scaling test: Wide $Q^2$ scans at fixed $x_B$ (larger $Q^2$ lever arm than previously & several values of $x_B$)
- Separation of Re and Im parts of DVCS cross-section amplitude

<table>
<thead>
<tr>
<th>kinematic</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>kin36_1</td>
<td>3.2</td>
<td>0.36</td>
</tr>
<tr>
<td>kin36_2</td>
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<td>0.36</td>
</tr>
<tr>
<td>kin36_3</td>
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<td>0.36</td>
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<tr>
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<td>0.48</td>
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<tr>
<td>kin48_4</td>
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<td>kin60_1</td>
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<td>0.60</td>
</tr>
<tr>
<td>kin60_2</td>
<td>6.1</td>
<td>0.60</td>
</tr>
<tr>
<td>kin60_3</td>
<td>8.4</td>
<td>0.60</td>
</tr>
<tr>
<td>kin60_4</td>
<td>9.0</td>
<td>0.60</td>
</tr>
</tbody>
</table>

100 days of beam (88 + 12 calibration)
DVCS at Jefferson Lab, Hall A – Apparatus

• Jlab: 12 GeV electron accelerator facility + 4 experimental Halls (A, B, C, D)

- Electron beam: e
- Liquid Hydrogen target: p
- Spectrometer: detect e’
- Calorimeter: detect γ
- p’ not detected

DVCS missing mass: $ep \rightarrow e’Xγ$

Missing mass$^2 = (e + p - e’ - γ)^2$

**Exclusivity** of the DVCS process is ensured by a cut on the **missing mass**.
Beam polarization measurement

- Moller & Compton polarization measurements
- Moller: $e^- - e^-$ scattering on dedicated Moller target (both $e^-$ polarized), measure counting asymmetry.
- Compton: $e^- - \gamma$ scattering (circularly polarized laser), measure counting asymmetry.

- Moller results finalized
- Compton analysis not finalized yet, discrepancies being investigated
- Fall 2016: beam polarization ~85%, and stable
Beam current measurement

- Used Beam Current Monitors: RF cavity in which the electron beam induces a current
- BCM calibration: induced current in cavity $\leftrightarrow$ beam current
- 2 BCMs: U (upstream) & D (downstream), connected to several amplification electronics: D $\rightarrow$ D1, D3, D10

- Beam current used: $10 \, \mu A \leq I \leq 20 \, \mu A$
- Unew & Dnew are noisier (electronics) $\rightarrow$ not used
- U1 & D1 are not linear $\leq 10 \, \mu A$ $\rightarrow$ not used
- D3 & D10 linear for $5 \, \mu A \leq I \leq 25 \, \mu A$
- D3 & D10 agree within 1%
- D10 stable against D3
- Conclusion: can rely on average of D3 & D10
**Trigger efficiency measurement**

- **Method:**
  - Use 2 out of 3 detectors as trigger
  - Upon trigger detection, check if particle detected in 3rd (left out) detector → Measure efficiency of 3rd (left out) detector
  - S0, S2 and Cerenkov efficiency > 99%
• Issue with one spectrometer magnet during Spring 2016, changed magnet during Fall 2016
  ➔ Optics calibrations
  ➔ **Good vertex resolution** ($\sigma = 3.5$ mm with spectrometer at 15.18 deg)
  ➔ **Good momentum resolution** ($\sigma_{dp/p} = 10^{-3}$)
Spectrometer acceptance study

• R-function: computes distance (R-value) of an event to the edges of the spectrometer 4D-acceptance.

• More efficient cut than four 1D-cuts (because of correlations).

• Cut on R-value: R-cut. Data and Monte Carlo event distributions must agree for R-value > R-cut.

• MC simulation will use R-cut to compute spectrometer acceptance.
Coincidence time correction

Corrected for:

- Trigger jitter (relative time between calorimeter and spectrometer triggers)
- Calorimeter blocks relative time (cabling)
- S2m paddles relative time
- Photons travel time in S2m
- Electron travel time

Good identification of calorimeter - spectrometer coincidence allows to remove accidentals.

Sigma = 6.6 ns

Sigma = 0.85 ns
Calorimeter energy calibration

- Proton detected in spectrometer, electron detected in calorimeter.
- Compute expected electron energy using detected proton (elastic) : $E_e'$.
- Reconstruct electron energy in calorimeter : $E_e$.
- Adjust calorimeter blocks calibration coefficients so that $E_e' = E_e$.

~3.6% energy resolution at 4.2 GeV
Calorimeter energy calibration

- Extremely fast initial loss of gain of the calorimeter blocks (radiation damage)
- Slower but **continuous loss of gain** afterward
- Small recovery after long down time
Calorimeter energy calibration

- Compute correction coefficients by reconstructing $\pi^0$ invariant mass.
- Optimize $\pi^0$ invariant mass mean value and resolution
- Correct calorimeter calibration coefficients between elastic calibrations

Block 151 is very sensitive to radiation damage

Before calibration
After calibration
Resolution: 10.3 MeV $\rightarrow$ 10.0 MeV

elastic calibration, elastic calibration
Dead time

Use scalers to compute dead time.

- Took specific runs to check that our dead time correction is correct
- Normalized “spectrometer electron” rates corrected by dead time are independent from beam current
  - Study ongoing…

\[
\text{Dead time} = 1 - \text{live time} \\
\text{Live time} = \frac{\text{live scaler rate}}{\text{raw scaler rate}}
\]

<table>
<thead>
<tr>
<th>I (µA)</th>
<th>Live Time</th>
<th>Normalized &quot;spectrometer electron&quot; rate / LT (Hz/µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.61</td>
<td>0.985</td>
<td>3.422</td>
</tr>
<tr>
<td>15.32</td>
<td>0.976</td>
<td>3.450</td>
</tr>
<tr>
<td>20.53</td>
<td>0.965</td>
<td>3.449</td>
</tr>
</tbody>
</table>
• Data acquisition ended in Fall 2016 with very good statistics

• Data analysis in progress
  • Calibrations complete
  • Lot of corrections/preliminary studies (almost) complete

• Next: DIS cross-section, MC simulation, $\pi^0$ subtraction, DVCS cross-section extraction, systematic uncertainties
  • 2018: Preliminary DVCS cross-sections extraction!
Thank You!

Questions?
Backup slides
Could not go back and complete kin48_[234] because of beam energy change over the summer 2016.

~50% of beam time allocation completed between 2014 and 2016.
DVCS missing mass:
\[ ep \rightarrow e'X\gamma \]

Missing mass\(^2 = (e + p - e' - \gamma)^2 \]

Exclusivity of the DVCS process is ensured by a cut on the missing mass.

\[ \pi^0 \] contamination, “looks like” a DVCS \( \gamma \)
• Jlab : High Luminosity → Challenge : **Pile-up**.
• **Analog Ring Sampler boards** : 1GHz Digitizer electronics, 128 ns samples.
  → Allows clear identification of DVCS photons and **pile-up resolution**.
  → Challenge : Large amount of data to deal with, **need “smart” trigger**.
DVCS Trigger System

• Level 1 – Electron Trigger in Spectrometer:
  • Coincidence: Scintillator paddle + Gaz Cerenkov detector

• If Level 1 trigger fired ➔ Level 2 – Coincidence with Calorimeter:
  • Calorimeter ARS boards freeze
  • Look for event in Calorimeter
  • Energy threshold

• If level 2 fired ➔ Event recorded (ARS encoding slow ➔ dead time)
• If level 2 NOT fired ➔ Event NOT recorded (no ARS encoding ➔ fast)
• Then, clear ARS boards and resume acquisition
Beam energy measurement

- Beam energy calculated from the settings of the accelerator. But calibration of the method is from the “6 GeV era” → Does not yield correct beam energy value for the “12 GeV era”.

- **Accurate beam energy measurement** : “Dispersive” method, measures beam bending in a dipole with known magnetic field.

- But beam energy shifts against time → A few beam energy measurements is not enough for several weeks/months of running.

- Solution : Dispersive beam energy measurement provides **correction scale factor** to the value calculated from the accelerator settings.

- Conclusion: reliable beam energy using “**calculated value * scale factor**”, run by run.

- $1 \leq \text{scale factor} \leq 1.003$
Quality analysis

Main rejection reasons:
• Very short runs / Very few “real” events recorded (beam trips)
• Abnormal trigger rates
• Abnormally high dead time

Fall 2016:
• Kin36_2: removed ~3.8% of total charge
• Kin36_3: removed ~5.3% of total charge
• Kin60_1: removed ~0.9% of total charge
• Kin60_3: removed ~1% of total charge

Spring 2016:
• Kin48_1: removed ~1.3% of total charge
• Kin48_2: removed ~0.5% of total charge
• Kin48_3: removed ~1% of total charge
• Kin48_4: removed ~3.9% of total charge

Fall 2014:
• Kin36_1: removed negligible percentage of total charge
Raster calibration

- Raster calibration complete
- Raster size calibrated against BPM readings.

\[ W^2 \text{ (GeV}^2) \]

\[ \rightarrow \text{ep to ep} \]

No raster correction

With raster correction
Raster calibration

- Failing raster power supply → loss of synchronization between raster 1 and 2.
- Calibration not possible (assumes raster 1 and 2 synchronized).
- > 50% of kin48_3 statistics affected.

- But simulation shows that error on variable reconstruction is smaller than experimental resolution.
Spectrometer – calorimeter synchronization

- Loss of synchronization between spectrometer and calorimeter during Fall 2016.
- 63 runs compromised (3.5 full days of production ~ 30% of kin60_1 statistics)
- Synchronization recovered using 6Hz clock signal sent to both spectrometer and calorimeter.
- Negligible loss of statistics.
Dead time

- Use scalers to compute dead time.
- Took specific runs to check that our dead time correction is correct
- Prescales effect: normalized DVCS rates well corrected by dead time (< 1%)
- Beam current effect: Normalized DVCS rates corrected by dead time are still dependent on beam current
  - Suspicion: Accidental coincidences calorimeter-spectrometer
  - Study in progress…

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<tr>
<th>Prescale</th>
<th>(I) ((\mu)A)</th>
<th>Live Time</th>
<th>DVCS rate (Hz)</th>
<th>((\text{Prescale} \times \text{DVCS rate}) / (I \times \text{Live Time})) (Hz/(\mu)A)</th>
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