Deeply Virtual Compton Scattering (DVCS) in Hall A

Hall A collaboration meeting

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Ohio University, Athens, Ohio

On behalf of DVCS collaboration
E12-06-114 DVCS/Hall A Experiment at 11 GeV

100 PAC days approved:
- High impact experiment for nucleon 3D imaging program
- High precision scaling tests of the DVCS cross section at constant $x_B$
- CEBAF12 will allow to explore for the first time the high $x_B$ region

50% of experiment planned & completed in 2014-2016

All calibrations (beamline+HRS+calo) completed DVCS & $\pi^0$ cross section analyses well underway

Analysis path:
- Jun’18: Preliminary results on $\pi^0$ at $x_B=0.36$
- Oct’18: Preliminary results on DVCS
- Nov’18: Short paper submitted to PRL on $\pi^0$
- Jan’19: Letter to PRL on DVCS
- Jul’19: Long paper to PRC (DVCS & pi0)
Generalized Parton Distributions (GPDs):

- Form Factors (FFs)
  - Spatial distribution
  - Momentum distribution

- Generalized Parton distribution (GPDs)
  - Spatial distribution
  - Longitudinal momentum distribution

- Patron Distribution Functions (PDFs)
  - Longitudinal momentum distribution
  - Spatial distribution

GPDs allows to access the 3D parton structure of Nucleon
Factorization

In Bjorken limit: \( Q^2 = -q^2 \rightarrow \infty \) \( \nu \rightarrow \infty \) \}

At fixed \( x_B = Q^2 / 2M\nu \)

Hard/perturbative Part:
- Calculable

Soft/non-perturbative Part:
- Nucleon structure is parametrized by GPDs

Handbag diagram for DVCS

Definition of variables:
- \( x \): longitudinal momentum fraction carried by struck quark.
- \( \xi \): longitudinal momentum transfer \( \approx x_B / (2 - x_B) \).
- \( t \): four momentum transfer related to \( b_\perp \) via Fourier transform.

Minimal \( Q^2 \) at which factorization holds must be tested

DVCS \( x \)-section \( \rightarrow \) GPDs \( \rightarrow \) Description of internal structure
**DVCS and Bethe-Heitler (BH):**

\[
\frac{d^5 \sigma}{dQ^2 dt dx_B d\phi_e d\phi} \propto |T_{DVCS} + T_{BH}|^2
\]

\[
= |T_{DVCS}|^2 + |T_{BH}|^2 + \mathcal{I}
\]

**At leading twist**

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

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

\[\text{Known to 1%} \quad \text{Bilinear combinations of GPDS} \]

\[\text{Linear combinations of GPDs} \]

Interference with BH gives access to Re and Im part of DVCS amplitude.
DVCS in Hall A

3 Generation of experiments so far

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Q^2 dependence study</td>
<td>Q^2 + beam energy dependence</td>
<td>High impact experiment for nucleon 3D imaging program</td>
</tr>
<tr>
<td>High precision scaling tests of the DVCS cross section at constant x_B</td>
<td>CEBAF12 will allow to explore for the first time the high x_B region</td>
<td></td>
</tr>
</tbody>
</table>

### Pushing to high Q^2 and x_B

<table>
<thead>
<tr>
<th>Period</th>
<th>Kinematic</th>
<th>Q^2</th>
<th>x_B</th>
<th>% target Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>F '14</td>
<td>361</td>
<td>3.20</td>
<td>0.36</td>
<td>100.0</td>
</tr>
<tr>
<td>F '16</td>
<td>362</td>
<td>3.60</td>
<td>0.36</td>
<td>100.0</td>
</tr>
<tr>
<td>F '16</td>
<td>363</td>
<td>4.47</td>
<td>0.36</td>
<td>100.0</td>
</tr>
<tr>
<td>Sp '16</td>
<td>481</td>
<td>2.7</td>
<td>0.48</td>
<td>100.0</td>
</tr>
<tr>
<td>Sp '16</td>
<td>482</td>
<td>4.37</td>
<td>0.48</td>
<td>56.6</td>
</tr>
<tr>
<td>Sp '16</td>
<td>483</td>
<td>5.33</td>
<td>0.48</td>
<td>76.4</td>
</tr>
<tr>
<td>Sp '16</td>
<td>484</td>
<td>6.90</td>
<td>0.48</td>
<td>53.0</td>
</tr>
<tr>
<td>F '16</td>
<td>601</td>
<td>5.54</td>
<td>0.60</td>
<td>100.0</td>
</tr>
<tr>
<td>F '16</td>
<td>602</td>
<td>6.10</td>
<td>0.60</td>
<td>0.0</td>
</tr>
<tr>
<td>F '16</td>
<td>603</td>
<td>8.40</td>
<td>0.60</td>
<td>100.0</td>
</tr>
<tr>
<td>F '16</td>
<td>604</td>
<td>9.00</td>
<td>0.60</td>
<td>0.0</td>
</tr>
</tbody>
</table>

F– Fall  Sp– Spring  Q^2 – in GeV^2

~50% of allocated 100 PAC days from Fall 2014, Spring 2016, and Fall 2016
E12-06-114 (DVCS3)

Exclusive DVCS: \( ep \rightarrow ep\gamma \)

\[ H(e, e'\gamma)X \]

Polarized \( e^- \) beam

Recoil proton reconstructed by \( MM^2 \)

208 PbF2 blocks

\[ M_{ep\rightarrow e'\gamma X}^2 = (k + p - k' - q_\gamma)^2 \]
Analysis status

Beam Studies
- Beam energy measurement
- Polarization measurement
- Raster calibration
- BCM/BPM calibration

High Resolution Spectrometer
- Trigger Efficiency
- Particle Identification
- Optics calibration
- Tracking Efficiency
- Acceptance Studies
- DIS x-section

Calorimeter
- Coincidence time correction
- Waveform analysis
- Elastic and $\pi^0$ calibration
- $\pi^0$ electroproduction (in progress)

DVCS Simulation

Q1 Status
Fall 2014: Old Q1 at full field
Spring 2016: Maximum current was limited to 2.8 GeV setting (detuned)
Fall 2016: Q1 saturated
Method developed to simulate one production run (~400,000 DVCS events) in about 2 hours using Auger

R-Function, calorimeter energy smearing, and photon reconstruction has been implemented

Simulation is moving towards the version control and will be on Git
Tracking efficiency (H. Rashad)

\[ \eta_{\text{MultiCluster}} = \frac{N_{2\text{M2S Electrons}}}{N(0\text{M4S+1M3S}) \text{ Electrons}} \]

\[ \eta_{\text{MultiTrack}} = \frac{N_{\text{MultiTrack Electrons}}}{N(0\text{M4S+1M3S}) \text{ Electrons}} \]

➢ Analyzer 1.5 has issues with reconstructing tracks for events with more than one cluster in any given VDC wire planes

➢ 3 cases: 0M4S, 1M3S, and 2M2S events yields single track reconstruction. Keep 0M4S and 1M3S exclude 2M2S

➢ ~5-10% events are reconstructed with more than one track and are excluded

Multi-cluster and Multi-track correction factors are mutually exclusive

\[ \eta_{\text{Final}} = \eta_{\text{MultiCluster}} + \eta_{\text{MultiTrack}} \]

Major correction
**Deadtime (S. Ali/ M. Dlamini)**

Dead time = 1 – live time

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

- Scalers to compute deadtime
- Dedicated runs to check the dead time correction
- Normalized DIS rates corrected by deadtime OK
- Normalized DVCS rates corrected by deadtime shows beam current dependence
  - Accidental coincidences (calorimeter-HRS)
  - Study in progress...

<table>
<thead>
<tr>
<th>I (μA)</th>
<th>Livetime (LT)</th>
<th>DIS rate /3.45 (Hz/μA)</th>
<th>DVCS rate /5.62 (Hz/μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.61</td>
<td>0.985</td>
<td>0.992</td>
<td>0.93</td>
</tr>
<tr>
<td>15.32</td>
<td>0.976</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>20.53</td>
<td>0.965</td>
<td>0.999</td>
<td>1.06</td>
</tr>
</tbody>
</table>

**DIS : S2 + Cer**

**DVCS : S2 + Cer (coincidence with Calo)**
Optics re-calibration Spring 2016 (F. Georges)

3 out of 4 kinematics were detuned (Q1)

LHRS optics calibration 16° → poor illumination → Poor reconstruction of target vertex

<table>
<thead>
<tr>
<th>Kin48_2 (Q1 at 62%, kscatt = 3.996 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration method</td>
</tr>
<tr>
<td>Run number</td>
</tr>
<tr>
<td>Run type</td>
</tr>
<tr>
<td>Target length</td>
</tr>
<tr>
<td>1st foil sigma (mm)</td>
</tr>
<tr>
<td>5th foil sigma (mm)</td>
</tr>
<tr>
<td>Distance foils 1-2 (cm)</td>
</tr>
<tr>
<td>Distance foils 2-3 (cm)</td>
</tr>
<tr>
<td>Distance foils 3-4 (cm)</td>
</tr>
<tr>
<td>Distance foils 4-5 (cm)</td>
</tr>
</tbody>
</table>

Rotation of the vertex-phi plane to correct vertex-phi dependence

Multiplication of the vertex by a scaling factor to reach ~15cm target length
Z vertex reconstruction for Fall 2016 kinematics

Work in progress for optimization of optics matrix for Fall 2016
Calorimeter energy calibration (M. Dlamini)

Elastic calibration (Invasive)

- Compute scattered electron energy, $E_{e'}$ (from detected p)
- Adjust calorimeter blocks' gain so that measured $e'$ energy = $E_{e'}$

Calorimeter blocks gain is lost due to radiation damage

Correct calorimeter blocks gain with $\pi^0$ calibration
Calorimeter energy calibration (F. Georges)

π⁰ calibration

After Calibration

Before Calibration

Resolution 10.3

→ 10.0 Mev

- Compute correction coefficient by reconstructing π⁰ invariant mass
- Optimize π⁰ invariant mass mean value and resolution
R-Function: computes Min. distance (R-value) of an event from edge of spectrometer

More efficient cut than multiple 1D cut due to correlations

Single R-cut value defines spectrometer acceptance

Data and MC event distribution must agree for R-value > R-cut

MC uses the R-cut to compute the spectrometer acceptance
Reproducing DIS cross section ensure our understanding of luminosity and e detection by HRS

\[
\frac{d^2 \sigma}{dxdQ^2} = \frac{N_c}{\mathcal{L}} \times \left( \frac{1}{\alpha \times \eta_{\text{virt}} \times \eta_{\text{exp}} \times \Gamma_{\text{DIS}}} \right)
\]

- Integrated luminosity
- \(\alpha\) term to modify phase space due to radiative effects
- \(\eta_{\text{virt}}\) term correcting virtual radiative effects
- \(\eta_{\text{exp}}\) term correcting detectors inefficiencies
- \(\Gamma_{\text{DIS}}\) phase space covered by LHRS
- \(N_c\) no. of event passing analysis cut (PID, vertex, track...)
**DIS x-section**


- Upto 5% uncertainty in reference cross-section

<table>
<thead>
<tr>
<th>Period</th>
<th>Kinematic</th>
<th>Relative difference(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2014</td>
<td>361</td>
<td>-2</td>
</tr>
<tr>
<td>Fall 2016</td>
<td>362</td>
<td>-8</td>
</tr>
<tr>
<td>Fall 2016</td>
<td>363*</td>
<td>-15</td>
</tr>
<tr>
<td>Spring 2016</td>
<td>481**</td>
<td>-2</td>
</tr>
<tr>
<td>Spring 2016</td>
<td>482</td>
<td>-7</td>
</tr>
<tr>
<td>Spring 2016</td>
<td>483</td>
<td>-5</td>
</tr>
<tr>
<td>Spring 2016</td>
<td>484</td>
<td>-6</td>
</tr>
<tr>
<td>Fall 2016</td>
<td>601**</td>
<td>-5</td>
</tr>
<tr>
<td>Fall 2016</td>
<td>603</td>
<td>+3</td>
</tr>
</tbody>
</table>

* Q1 saturation effect
** atypical run to run stability

Work in progress..
**π⁰ electroproduction (M. Dlamini)**

- Experimental setup allows exclusive π⁰ events
- Provides interesting and complementary insight into GPDs of nucleon

Other cuts:

→ Electron PID (same as DIS)
→ Cut on photon energy, $E_\gamma > 1.2$ GeV
→ Accidental subtraction

[-2, 2] ns window cut
\( \pi^0 \) electroproduction (M. Dlamini)
simulation–data

\( \pi^0 \) Mass - kin36_1

```
Data in good agreement with simulation
```
\( \pi^0 \) electroproduction (M. Dlamini)
\((\pi^0 \) data sample)
Summary and outlook

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Acknowledgments:
Hall A DVCS Collaboration
Hall A Collaboration
Hall A technical staff
Accelerator staff

THANK YOU!
GPDs: Quarks helicity and nucleon spin orientation:

Nucleon helicity conserving

Average over quark helicity

Unpolarized

Nucleon helicity non-conserving

Difference of quark helicity

Polarized

\[ Q^2 = 1.5, 1.9, 1.75 \text{ GeV}^2, \quad x_B = 0.36 \]

M. Guidal et al 2013 Rep. Prog. Phys. 76 066202
**Definition of R-value**

- If the test point is inside the polygon, R-value > 0.
- If the test point is outside the polygon, R-value < 0.
- If the test point is on the boundary of the polygon, R-value = 0.

### CaselCondition| $d_{xy,ij}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$L_{ij}^2 + d_{i}^2 - d_{j}^2 &gt; 0$ and $L_{ij}^2 - d_{j}^2 &gt; 0$</td>
</tr>
<tr>
<td>b</td>
<td>$L_{ij}^2 + d_{i}^2 - d_{j}^2 \leq 0$ or $L_{ij}^2 - d_{j}^2 \leq 0$</td>
</tr>
</tbody>
</table>

Trigger efficiency studies (H. Rashad)

- DVCS production is triggered by S2M && Cherenkov in coincidence with DVCS calorimeter
- S0, S2M, and Cherenkov all have > 99% efficiency