Deeply Virtual Compton Scattering at Jefferson Lab

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Outline

• Introduction – physics motivations
• Experimental setup
• High Resolution Spectrometer optics calibration
• Calorimeter $\pi^0$ calibration
Internal structure of the proton

Proton

Quark

Gluon

Spatial distribution ?
Momentum distribution ?
Spin structure ?

Electron – proton collisions allow to probe the internal structure of the proton.
Generalized Parton Distributions (GPDs)

- Elastic Scattering ($ep \rightarrow e'p'$) $\rightarrow$ Elastic Form Factors $\rightarrow$ Spatial distribution
- Inelastic Scattering ($ep \rightarrow e'X$) $\rightarrow$ Parton Distribution Functions $\rightarrow$ Momentum distribution
- DVCS ($ep \rightarrow e'p'\gamma$) $\rightarrow$ Generalized Parton Distributions $\rightarrow$ Spatial-Momentum correlations & Spin structure
Deeply Virtual Compton Scattering (DVCS)

**DVCS** : \( ep \rightarrow e'p'\gamma 

**Hard part**
(QED, can be computed)

**Soft part**
Parametrized by GPDs

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

DVCS cross section (~occurrence probability) measurement \( \rightarrow \) access GPDs
\( \rightarrow \) Description of the proton internal structure
DVCS at Jefferson Lab, Hall A (2014-2016)

- 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 $\gamma$
- $p'$ not detected

DVCS (ep $\rightarrow$ e'$p'\gamma$)
High Resolution Spectrometer (HRS) optics calibration
The HRS focal plan

Detector package ~ camera film

Magnets ~ camera lenses

Focal plan: “picture” of events happening at the target.

Detected electrons at the focal plan, measured:
- Position \((x_{fp}, y_{fp})\)
- Direction \((dx_{fp}/dz_{fp}, dy_{fp}/dz_{fp}) = (\theta_{fp}, \phi_{fp})\)

At the target, to be reconstructed:
- Event vertex (= position) \(y_{tg}\)
- Electron scattering angles \((\theta_{tg}, \phi_{tg})\)
- Electron momentum \(\delta_{tg}\)

4 variables in focal plan coordinate system

↓

4 variables in target coordinate system
The optics matrix

1\textsuperscript{st} order approximation:

\[
\begin{bmatrix}
\delta \\
\theta \\
y \\
\phi
\end{bmatrix}_{tg} = 
\begin{bmatrix}
\langle \delta | x \rangle & \langle \delta | \theta \rangle & 0 & 0 \\
\langle \theta | x \rangle & \langle \theta | \theta \rangle & 0 & 0 \\
0 & 0 & \langle y | y \rangle & \langle y | \phi \rangle \\
0 & 0 & \langle \phi | y \rangle & \langle \phi | \phi \rangle
\end{bmatrix}
\begin{bmatrix}
x \\
\theta \\
y \\
\phi
\end{bmatrix}_{fp}
\]

Full polynomial expression, order 5:

\[
y_{tg} = \sum_{i=1}^{m} \sum_{j,k,l} C_{i}^{Y_{jkl}} x_{fp}^{i} \theta_{fp}^{j} y_{fp}^{k} \phi_{fp}^{l}
\]

\[i + j + k + l \leq 5\]

\[C_{i}^{Y_{jkl}} \text{“Optics matrix coefficients”}\]

- Need calibration if magnets tuning is changed.
- Spring 2016 : magnet issue
Step 1: vertex reconstruction calibration

- Data taken on a 5 thin carbon foils target (1mm thick)
- Expected vertex values $y^{0}_{lg}$, correlated to precise areas of the focal plan
- Computation of the new optics matrix coefficients $C^{Y_{jkl}}_{i}$ by minimizing the aberration function $\Delta(y)$

$$\Delta(y) = \sum_{s} \left[ \sum_{j,k,l} Y_{jkl} \frac{\theta^{j}_{fp} y^{k}_{fp} \phi^{l}_{fp}}{\sigma^{s}_{y}} - y^{0}_{lg} \right]^2$$

$$Y_{jkl} = \sum_{i=1}^{m} C^{Y_{jkl}}_{i} x^{i}_{fp}$$
Step 2: angles reconstruction calibration

- Thick metal plate with holes inserted in front of the LHRS entrance (Sieve)
  - Holes = expected values for electron scattering angles $\theta_{tg}$ and $\phi_{tg}$, correlated to precise areas of the focal plan
  - Computation of new optics matrix coefficients by minimization of aberration functions $\Delta(\theta)$ and $\Delta(\phi)$
Step 3 : momentum reconstruction calibration

• Data taken on an LH$_2$ target, elastic scattering ep $\rightarrow$ ep setting
  • Constrained system: known scattering angle = known scattering momentum
• “Delta Scan”
  • LHRS angle fixed
  • 5 runs varying HRS central momentum setting (central momentum, $\pm 2\%$, $\pm 4\%$)
    • Elastic momentum-scattering angle correlation $\rightarrow$ each momentum value correlated to precise and different focal plan areas

$\rightarrow$ Expected values for momentum $\delta_{tg}$, correlated to precise areas of the focal plan
$\rightarrow$ Computation of new optics matrix coefficients by minimization of aberration function $\Delta(\delta)$. 
HRS optics – Preliminary results

- Remaining issue with vertex reconstruction on target edges
- Corrections: work in progress
Calorimeter $\pi^0$ calibration
Calorimeter $\pi^0$ calibration

• 208 PbF$_2$ crystals
• Measure photons energy deposit in each crystal

• Radiation damages: PbF$_2$ crystals become darker
  → Loss of gain
  → Need to compute new correction coefficients often to compensate
  → $\pi^0$ calibration, uses $\pi^0$ mass reconstruction

• $\pi^0 \rightarrow \gamma_1 + \gamma_2$
• $m^2_{\pi} = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{\gamma_1\gamma_2})$
Calorimeter $\pi^0$ calibration

- Correction coefficients $\rightarrow$ optimize mean value + $\pi^0$ reconstructed mass resolution

- Minimize:

$$F = \sum_{i=1}^{N}(m_i^2 - m_{\pi^0}^2)^2 + \lambda \sum_{i=1}^{N}(m_i^2 - m_{\pi^0}^2)$$

$$m_i^2 = 2 \left( \sum_{i=0}^{N_1} c_i E_i \right) \left( \sum_{j=0}^{N_2} c_j E_j \right) (1 - \cos \theta_{12})$$

Correction coefficients

$$\frac{\partial F}{\partial C_k} \bigg|_{\forall k \in [0;208]} = 0$$

Linear system: 208 equations and 208 variables

Before calibration

Resolution: 10.3 MeV $\rightarrow$ 10.0 MeV

After calibration

Photon 1 Photon 2

November 24-25

Reconstructed $\pi^0$ mass (GeV)
Calorimeter $\pi^0$ calibration – Preliminary results

- ~30% total gain loss at the end of the experiment
- Issues with edges and few peculiar crystals

Crystal 35 is very sensitive to radiation damage
Summary and Outlook

• Data acquisition ended Fall 2016
• Data analysis in progress
  • Many Calibrations/Corrections studies almost complete
    • HRS Optics
    • Calorimeter $\pi^0$ calibration
    • Wave form analysis (= how to identify and fit raw signals)
    • …

• Then:
  • data decoding/analysis using completed calibrations/corrections
  • DVCS cross sections extraction
  • GPDs (long term)
Thank You!

Questions?
DVCS in Hall A - Apparatus

\[ ep \rightarrow e'p'\gamma \]
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.
HRS optics calibration – focal plan area issue

- Production run setting - HRS angle : 37.1 deg
- Optics calibration run - HRS angle : 16.6 deg

- Optics calibration run taken at small angle → areas of focal plan were not illuminated
  → Poor calibration of the not illuminated area → Poor vertex reconstruction
  → Poor vertex reconstruction on target edges for production runs → reconstructed target is too short
Calorimeter $\pi^0$ calibration

- Initial calibration (elastic calibration):
  - Time consuming (~1 day)
  - Requires experimental setup changes
  - Cannot take DVCS data while calibrating
- $\pi^0$ calibration uses $\pi^0$ detected while taking DVCS data.
  - Can be done very often and after the actual data taking.
  - No beam time loss.

$\pi^0$ invariant mass (with no correction)
DVCS in Hall A - Goal

- Timeline:
  - E00-110/E03-106 (2004) : first round of dedicated experiments (Q² dependence study)
  - E07-007/E08-025 (2010) : second round of dedicated experiments (Q² dependence study + beam energy dependence)
  - E12-06-114 (2014 - 2016) : ~50% PAC days completed

- E12-06-114 goals:
  - Scaling test : Wider Q² scans at fixed x_B (larger Q² lever arm than in 2010 & several values of x_B)
  - Separation of Re and Im parts of DVCS cross-section amplitude

100 PAC days (88 + 12 calibration)
The DVCS + Bethe-Heitler interactions $e p \rightarrow e' p' \gamma$

$Q^2 = - (e' - e)^2$ : virtuality of $\gamma^*$

$\nu = E - E'$, energies of the electron before and after scattering

$x_B = \frac{Q^2}{2M\nu}$ (NB: $x_B \neq x$)

$\xi = \frac{x_B}{2-x_B}$

$-2\xi$ : longitudinal momentum transfer to the struck quark.

$t = (p - p')^2$ : squared momentum transfer to the proton

In the limit $Q^2 \rightarrow \infty$ and $\nu \rightarrow \infty$ but fixed $x_B$ (Bjorken limit), the virtual photon $\gamma^*$ interacts with a single quark in the proton.
DVCS and Bethe-Heitler

At leading twist:

\[ d^5 \sigma^\rightarrow - d^5 \sigma^\leftarrow = \Im \left( T^{BH} \cdot T^{DVCS} \right) \]

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

Known to 1%