New results on Deeply Virtual Compton Scattering at HERA

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- Deeply Virtual Compton Scattering (DVCS)
- Generalized Parton Distributions (GPDs)
- DVCS Measurements at HERA
  - Cross Section Measurements at H1 and ZEUS
  - Azimuthal Asymmetries at HERMES
- Summary and Outlook
**Deeply Virtual Compton Scattering (DVCS)**

**Simplest (hard exclusive) process:** \( \gamma^* p \rightarrow p' \gamma \)

**Deeply virtual photon generated by lepton scattering**
\[ e p \rightarrow e' p' \gamma \text{ (DVCS)} \]

- **Longitudinal momentum fractions:**
  \[ x \in [-1, 1] \text{ (not accessible)} \]
  \[ \xi \approx x_B/(2 - x_B) \]

- \( t = (q - q')^2 \)
  \( (\gamma^* \rightarrow \gamma \text{ Momentum transfer}) \)

- \( Q^2 = -q^2 \)

**DVCS-amplitudes** can be expressed in terms of GPDs.

**GPDs** accessible in exclusive reactions \( \Rightarrow \) Use the simplest one . . .
GPDs ↔ Nucleon Structure

GPDs \((H, \tilde{H}, E, \tilde{E})\): Parameterization of the nucleon structure

Related to known quantities:
GPDs in the limit \(t \to 0\):
\[H(x, 0, 0) = q(x)\]

First moments of GPDs:
\[\int_{-1}^{1} dx \ H(x, \xi, t) = F_1(t)\]

Only access to unknown quantities:
Second moments of GPDs:
\[J_q = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} dx \ x \ [H^q(x, \xi, t) + E^q(x, \xi, t)]\]
DVCS–BH INTERFERENCE

**DVCS** final state \( e + p \rightarrow e' + p' + \gamma \) is indistinguishable from the **Bethe-Heitler Process** (BH) \( \rightarrow \) **Amplitudes add coherently**

\[
\begin{align*}
\text{H1, ZEUS, HERMES, CLAS} \quad &\quad \text{H1, ZEUS}
\end{align*}
\]

**Photon-Production cross section:**

\[
d\sigma \propto \left| \tau_{\text{DVCS}} + \tau_{\text{BH}} \right|^2 = \left| \tau_{\text{DVCS}} \right|^2 + \left| \tau_{\text{BH}} \right|^2 + \left( \tau^*_{\text{DVCS}} \tau_{\text{BH}} + \tau^*_{\text{BH}} \tau_{\text{DVCS}} \right)
\]
DVCS MEASUREMENTS AT HERA

\[ d\sigma \propto |\tau_{BH}|^2 + \left( \frac{\tau_{DVCS}^* \tau_{BH} + \tau_{BH}^* \tau_{DVCS}}{I} \right) + |\tau_{DVCS}|^2 \]

\[ |\tau_{BH}|^2 \text{ CALCULABLE IN QED WITH THE KNOWLEDGE OF THE FORM FACTORS} \]

\[ I \propto \pm \left( c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi) \right) \]

**DVCS CROSS SECTION (H1, ZEUS):**
**MEASUREMENT INTEGRATED OVER \( \phi \)**
\( \rightarrow I = 0 \) (AT TWIST–2), SUBTRACT \( |\tau_{BH}|^2 \)

**AZIMUTHAL ASYMMETRIES (HERMES):**
**DVCS AMPLITUDES DIRECTLY ACCESSIBLE VIA \( I \)**
(GPDs ENTER IN LINEAR COMBINATIONS IN AMPLITUDES)
DVCS CANDIDATE SAMPLE

COLLIDER:

MC: LO PREDICTION
BY FFS AT $t = t_{\text{min}}$
ASSUME $e^{bt}$
WITH $b = 7 \text{ GeV}^{-2}$

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**Cross Section Extraction**

**H1 Preliminary**

- **$ep \rightarrow ep\gamma$ Total Cross Section Extraction:**

\[
\frac{d\sigma_{\text{bin}}}{dQ^2} = \frac{N_{\text{bin}} - N_{\text{backg}} - N_{\text{diss,p}}}{\epsilon A \Delta Q^2 L} (1 + \delta_{\text{rad}})
\]

- **$ep \rightarrow ep\gamma$ DVCS Cross Section Extraction:**

  $I \approx 0$, subtract BH

- **$\gamma^* p \rightarrow p\gamma$ Cross Section Extraction:** Photon flux factor $\Rightarrow$

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**New Preliminary Result**

NLO QCD predictions based on GPDs

\[ b = b_0(Q^2) \]

\[ 5 < b_0 < 9 \text{ GeV}^{-2} \]

Models describe data, but normalization uncertainty

⇒ **Measure** \( t \)-dependence

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ALL H1 AND ZEUS RESULTS

At $b = 7$ GeV$^{-2}$:

**Color dipole model DD (also Favart–Machado) and GPD based model describe the data**

$W^\delta$ fit:

- **H1 Prel**: $0.98 \pm 0.44$
- **ZEUS $e^+$**: $0.75 \pm 0.15^{+0.08}_{-0.06}$

⇒ Indicates hard regime

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AZIMUTHAL ASYMMETRIES AT HERMES

\[ d\sigma \propto |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + (\tau_{DVCS}^* \tau_{BH} + \tau_{BH}^* \tau_{DVCS}) \]

\[ I \propto \pm \left( c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi) \right) \]

Beam–Charge Asymmetry (BCA) and Beam–Spin Asymmetry (BSA) at leading twist:

BCA : \( d\sigma(e^+p) - d\sigma(e^-p) \sim c_1^I \cos(\phi) \sim \cos(\phi) \times \text{Re} M^{1,1} \)

BSA : \( d\sigma(\overrightarrow{e^+}p) - d\sigma(\overleftarrow{e^+}p) \sim s_1^I \sin(\phi) \sim \sin(\phi) \times \text{Im} M^{1,1} \)

⇒ **Real and Imaginary Part** of the helicity conserving amplitude \( M^{1,1} \) can be accessed via Beam–Charge and Beam–Spin Asymmetry (Other Amplitudes → \( \cos 2\phi, \cos 3\phi, \sin 2\phi \))

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**HERMES Event Selection**

**Fixed Target:**

**Beam:**

27.6 GeV

\( e^+ \) AND \( e^- \)

\( \langle P \rangle \approx 55\% \)

**No recoil detection \( \Rightarrow \)**

**Exclusivity via missing mass \( \Rightarrow MC \)**

\(|\tau_{DVCS}|^2 < < |\tau_{BH}|^2\)

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Beam–Spin Asymmetry (BSA)

\[ A_{LU}(\phi) = \frac{1}{<|P_b|>} \frac{\bar{N}(\phi)}{N(\phi)+N(\phi)} \]

\[ e^+ p \rightarrow e^+ \gamma X \quad (M_x < 1.7 \text{ GeV}) \]

HERMES PREL. 2000 (refined)

\[ P_1 + P_2 \sin \phi + P_3 \sin 2\phi \]

\[ \phi \text{(rad)} \]

\[ A_{LU} \]

\[ \sin(\phi) \text{--MOMENT IN NON–EXCLUSIVE REGION: SMALL AND SLIGHTLY POSITIVE (→ π0)} \]

\[ A_{LU} \text{ IN EXCLUSIVE BIN: EXPECTED sin(\phi) DEPENDENCE ⇒ Im } M^{1,1} \]

(Results from 1996/97 → PRL 87, 182001 (2001))

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**Beam-Charge Asymmetry (BCA)**

\[
A_C(\phi) = \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)} \propto I \propto \pm (c_0^I + \sum_{n=1}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi))
\]

\[
\chi^2/\text{ndf} : 11.47/8
\]

\[
c_0 = 0.009 \pm 0.020 \text{ (stat)}
\]

\[
c_1 = 0.059 \pm 0.028 \text{ (stat)}
\]

\[
s_1 = 0.094 \pm 0.028 \text{ (stat)}
\]

**HERMES PRELIMINARY** (\(\langle -t_c \rangle = 0.12 \text{ GeV}^2\))

\[
e^\pm p \to e^\pm \gamma X \quad (M_X < 1.7 \text{ GeV})
\]

\[
A_C = c_0 + c_1 \cos \phi + s_1 \sin \phi
\]

**HERMES PRELIMINARY** (refined analysis, \(\langle -t_c \rangle = 0.12 \text{ GeV}^2\))

\[
e^\pm p \to e^\pm \gamma X
\]

\[
A_C \quad \text{in exclusive bin: \textbf{Expected}}
\]

\[
\cos(\phi) \text{ dependence} \Rightarrow \Re M^{1,1}
\]

\[
\sin \phi \text{ due to polarized beam}
\]

**cos(\phi)--Moments zero at higher missing mass**

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**The latest News! → BCA versus \( t \)**

**More:**

**First BCA on deuterium!**

Coherent production only in first \( t \)-bin (\( \approx 40\% \))

→ No effect seen

→ \( \approx \) p-target

Difference in last bin

(Neutron resonances, neutron)

(BSA on deuterium, neon → hep ex/0212019)

**GPD model**

(Vanderhaeghen et al.)

Tiny \( e^-p \) sample (\( L \approx 10 \text{ pb}^{-1} \))

⇒ \( t \)-dependence of BCA has high sensitivity to GPD models!

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**SUMMARY**

- **DVCS-Cross-Sections/Amplitudes** ⇒ GPDs
  ⇒ Structure of Hadrons

- **HERA:** First measurements of cross-sections and azimuthal asymmetries

- **HERA I:** Results in agreement with different models
  ⇒ Basic Concept works ⇒ first constraints on models

- **HERA II:**
  - Also asymmetry measurements at H1,ZEUS (spin rotators)
  - Ensure exclusivity ⇒ detect the proton
    (VFPS at H1, Recoil detector at HERMES)
  - Statistics . . .

⇒ **HERA** (wide kinematic range, $e^+/e$, polarized beam) is the place to study DVCS/GPDs