HERA DVCS Working Group Meeting
Hamburg, 28.10.2009

Caroline Riedl
for the HERMES Collaboration
Outline:
DVCS at HERMES

- HERMES and HERA
- Generalized Parton Distributions
- Azimuthal Asymmetry Amplitudes
- The Recoil detector upgrade
HERMES and HERA

Tracking
momentum resolution: ≤ 2%
angular resolution: 0.3...0.6 mrad

Particle IDentification
electron ID: 98-99%
hadron contamination <1%
RICH: 2...15 GeV

Sokolov-Ternov mechanism

\( P_B = 30...65\% \)
2 beam helicities
e\(^+\) and e\(^-\)

\( e^\pm \)
27.6 GeV
HERMES and HERA

27.6 GeV $e^\pm$

Tracking
momentum resolution: $\leq 2\%$
angular resolution: 0.3...0.6 mrad

| $H$, $H$, $D$ |
| H, D |
| He, N, Ne, Kr, Xe |

Particle IDentification
- electron ID: 98-99%
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Sokolov-Ternov mechanism
- $P_B = 30...65\%$
- 2 beam helicities
- $e^+$ and $e^-$

Comparison of rise time curves
- Transverse Polarimeter
- Longitudinal Polarimeter
**Generalized Parton Distributions**

- **PDFs:** longitudinal momentum
  - forward limit $\xi=0$, $t=0$: $H^q(x, 0, 0) = q(x)$

- **Form Factors:** transverse position
  - moments of GPDs: $\int_{-1}^{1} dx H^q(x, \xi, t) = F_1^q(t)$

- **Nucleonic Spin:** total angular momentum
  - Ji relation:
    
    $$J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \ x [H^q(x, \xi, t) + E^q(x, \xi, t)]$$

**Leading twist, quark chirality conserving, spin-1/2**

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leading twist, quark chirality conserving, spin-1/2

**Skewing:** $\xi \neq 0$

off forward limit

$\int_{-1}^{1} dx H^q(x, \xi, t) = F_1^q(t)$
Generalized Parton Distributions

"Nucleon tomography"

**PDFs**: longitudinal momentum
forward limit $\xi=0$, $t=0$: $H^q(x, 0, 0) = q(x)$

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| $J^P$=1$^-$ mesons | $J^P$=0$^-$ mesons |

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Generalized Parton Distributions

PDFs: longitudinal momentum
forward limit $\xi=0, t=0$: $H^q(x, 0, 0) = q(x)$

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moments of GPDs:
$$\int_{-1}^{1} dx H^q(x, \xi, t) = F^q_1(t)$$

"Nucleon tomography"

Nucleonic Spin: total angular momentum

Ji relation:
$$J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \ x [H^q(x, \xi, t) + E^q(x, \xi, t)]$$

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Skewing: $\xi \neq 0$ off forward limit

"Nucleon tomography"
Generalized Parton Distributions

PDFs: longitudinal momentum
forward limit \( \xi=0, t=0: \) \( H^q(x, 0, 0) = q(x) \)

Form Factors: transverse position
moments of GPDs:
\[
\int_{-1}^{1} dx H^q(x, \xi, t) = F_1^q(t)
\]

leading twist, quark chirality conserving, spin-1/2

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carbide: impact parameter

“Nucleon tomography”

angular momentum

\[
H^q(x, \xi, t) + E^q(x, \xi, t)
\]
Generalized Parton Distributions

PDFs: longitudinal momentum
forward limit $\xi=0$, $t=0$: $H^q(x, 0, 0) = q(x)$

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$H$, $E$, $\tilde{H}$, $\tilde{E}$

Skewing: $\xi \neq 0$ off forward limit

$J^p=1^-$ mesons $J^p=0^-$ mesons
Generalized Parton Distributions

PDFs: longitudinal momentum
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Deeply Virtual Compton Scattering

\[ \sigma_{\gamma^*\gamma N} \sim |\tau_{\text{DVCS}}|^2 + |\tau_{\text{BH}}|^2 + \tau_{\text{DVCS}}\tau_{\text{BH}}^* + \tau_{\text{DVCS}}^*\tau_{\text{BH}} \]

Contribution at colliders.

Fixed target:

\[ |\tau_{\text{DVCS}}|^2 \ll |\tau_{\text{BH}}|^2 \]

Exactly calculable in QED given the nucleon elastic form factors \( F_1 \) and \( F_2 \)

Holographic principle:

• BH reference amplitude magnifies DVCS
• Measure magnitude \( A \) and phase \( \phi \) of DVCS amplitude \( \tau_{\text{DVCS}} = Ae^{i\phi} \)

DVCS-BH interference term
Deeply Virtual Compton Scattering

\[ \sigma_{\gamma^* \gamma N} \sim |T_{\text{DVCS}}|^2 + |T_{\text{BH}}|^2 + T_{\text{DVCS}} T_{\text{BH}}^* + T_{\text{DVCS}}^* T_{\text{BH}} \]

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Belitsky, Müller, hep-ph/0206306

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Azimuthal Dependences in $\gamma^* N \rightarrow \gamma N$

- Unpolarized target
- Lepton beam with charge $C_B$ and polarization $P_B$

Fourier expansion in azimuthal angle $\phi$

\[
|\mathcal{T}_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)
\]

\[
|\mathcal{T}_{DVCS}|^2 = K_{DVCS} \left[ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi) \right]
\]

\[
\mathcal{I} = \frac{C_B K_{I}}{P_1(\phi)P_2(\phi)} \left[ \sum_{n=0}^{3} c_n^{I} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{I} \sin(n\phi) \right]
\]

Wanted: Fourier coefficients $s_n$ and $c_n$ of BH, DVCS, and $I$ terms
Measured Azimuthal Asymmetries in DVCS

Born cross-section:
\[ \sigma(\phi; P_B, C_B) = \sigma_{UU}(\phi) \cdot [1 + P_B A_{LU}^{DVCS}(\phi) + C_B P_B A_{LU}^T(\phi) + C_B A_C(\phi)] \]

Beam helicity asymmetries

Old approach at HERMES and CLAS: single charge BSA

\[ A_{LU}(\phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \]

no separate access to \( s_1^q \) and \( s_1^{DVCS} \)

Beam charge asymmetry

BSA: projects out imaginary part of \( \tau_{DVCS} \)

BCA: projects out real part of \( \tau_{DVCS} \)

\[ A_C(\phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \]
Measured Azimuthal Asymmetries in DVCS

Beam helicity asymmetries

Old approach at HERMES and CLAS: single charge BSA

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no separate access to \( s_1^q \) and \( s_1^{DVCS} \)

New approach at HERMES: \( s_1^q \) and \( s_1^{DVCS} \) can be disentangled

Charge difference BSA:

\[ A_{LU}^I(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) - (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})} \]

Beam charge asymmetry

BCA:
projects out real part of \( \tau_{DVCS} \)

Charge average BSA:

\[ A_{LU}^C(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})} \]
From Azimuthal Asymmetries to GPDs

Express asymmetries in terms of Fourier coefficients $c$ and $s$
\[\equiv\text{asymmetry amplitudes}\]

Compton Form Factors (CFFs)
\[\mathcal{F}(\xi, t) = \sum_q \int_{-1}^{1} dx \, C_q^\mp(\xi, x) F^q(x, \xi, t)\]

Define linear combination of CFFs:
\[C_{\text{unp}}^\tau = F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}\]

$F_1(t), F_2(t)$: Dirac, Pauli nucleonic form factors

At leading twist level (twist-2):
\[c^\tau_1 \propto \frac{\sqrt{-t}}{Q} \Re \left[ C_{\text{unp}}^\tau \right] \propto - \frac{Q}{\sqrt{-t}} c^\tau_0\]
\[s^\tau_1 \propto \frac{\sqrt{-t}}{Q} \Im \left[ C_{\text{unp}}^\tau \right] \]

BCA

BSA

constant term
DVCS at HERMES 1996-2005 (w/o Recoil)

Detected particles: electron and photon

Missing mass technique for \( ep \rightarrow eX\gamma \)

\[ M_X^2 = (p+q-p_\gamma)^2 \]

- Hydrogen target: 25k events (400 pb\(^{-1}\))
- Unpolarized deuterium: 15k events (300 pb\(^{-1}\))
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Detected particles:

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**Diagram: **

- Field clamps
- Drift chambers
- Target cell
- Steel plate
- Magnetic field
- Positron
- Electron
- Hydrogen target: 25k events (400 pb$^{-1}$)
- Resonant excitation: $X = \Delta^+$
- Unpolarized deuterium: 15k events (300 pb$^{-1}$)
- $X = \pi^0 + ...$
- $p\pi^0$
- $n\pi^+$

**Graph: **

- 1000N/N$_{DIS}$
- $M_X^2 (GeV^2)$
- $e^+$ data
- $e^-$ data
- MC sum
- Elastic BH
- Associated BH
- Semi-inclusive
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$1000N/N_{Bjj}$

$M_X^2$ (GeV$^2$)
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- \( e^- \) data
- MC sum
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- associated BH
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\[ X = p \]

Resonant excitation: \( X = \Delta^+ \)

\[ X = \pi^0 + \ldots \]

Hydrogen target:
- 25k events
  - (400 pb\(^{-1}\))

Unpolarized deuterium:
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DVCS Beam Helicity Asymmetries

HERMES

\( \propto \Im [F_1 \mathcal{H}] \)

\( ep \rightarrow ep\gamma \)


Higher twist (twist-3)

Fraction of resonant excitation

all data 1996-2005, arXiv:0909.3587, accepted by JHEP
DVCS Beam Charge Asymmetry

\[ \propto -A_C \cos \phi \]

Constant term:

\[ \propto \Re \left[ F_1 \mathcal{H} \right] \]

\[ \leftrightarrow \text{Higher twist (twist}-3\text{)} \]

\[ \leftrightarrow \text{Gluon leading twist} \]

HERMES

\[ ep \rightarrow ep \gamma \]
DVCS Beam Charge Asymmetry

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constant term:

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HERMES

ep → epγ

\[ \propto \Re \left[ F_1 \mathcal{H} \right] \]

Also available:
2-dim \((x_B,t)\) binning
(BSAs and BCA)

Higher twist (twist-3)

Gluon leading twist

\[ \propto - A_C \cos \phi \]

\[ \propto \Re \left[ F_1 \mathcal{H} \right] \]
**DVCS on Nuclear Targets**

- How does the nuclear environment modify parton-parton correlations?
- How do nucleon properties change in the nuclear medium?
- DVCS in coherent region: new insights into ‘generalized EMC effect’?

- Nuclear GPDs ≠ GPDs of free nucleon
- Enhancement of effect when leaving forward limit?
- Strong increase of real part of $\tau_{DVCS}$ with atomic mass number $A$?
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<tr>
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HERMES measurements on nuclear targets

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+ deuterium, spin-1, 300 pb$^{-1}$
DVCS Beam Charge Asymmetry on hydrogen and deuterium

HERMES PRELIMINARY

Acceptance & smear → sys error

overall -t (GeV²) x_B Q² (GeV²)
DVCS Beam Charge Asymmetry on hydrogen and deuterium

HERMES PRELIMINARY
Accep & smear → sys error

$e^\pm d \rightarrow e^\pm \gamma X$

$e^\pm p \rightarrow e^\pm \gamma X$

$A_C \cos(0 \phi)$

$A_C \cos(2 \phi)$

$A_C \cos(3 \phi)$

overall  

$-t$ (GeV$^2$)  

$x_B$  

$Q^2$ (GeV$^2$)

low $t$: coherent

Proton

elicastic

inelastic

Nucleus

coherent

quasi-elastic

incoherent

Caroline Riedl (DESY), HERA DVCS Working Group Meeting, Hamburg 28.10.2009
DVCS Beam Charge Asymmetry on hydrogen and deuterium
Select for each target two samples (t-cutoffs):

- **coherent enriched**
  
  \( \approx 65\% \) coherent fraction

- **incoherent enriched**
  
  \( \approx 60\% \) incoherent fraction
Select for each target two samples (t-cutoffs):
- coherent enriched
  (∼65% coherent fraction)
- incoherent enriched
  (∼60% incoherent fraction)
Select for each target two samples (t-cutoffs):

- coherent enriched
  \( \approx 65\% \) coherent fraction

- incoherent enriched
  \( \approx 60\% \) incoherent fraction

\( \Rightarrow \) no enhancement of \( T_{DVCS} \)
DVCS Transverse Target Spin Asymmetry $A_{UT}(\phi, \phi_s)$

$A_{UT}$: the only DVCS asymmetry on the proton for which **GPD E is not suppressed**

(JLab Hall-A: BSA on neutron)

**HERMES**: transversely polarized hydrogen, 170 pb$^{-1}$, 2 beam charges

- Separation of DVCS and interference terms possible:

$$A_{UT}^I(\phi, \phi_s) \propto [d\sigma^+(\phi, \phi_s) - d\sigma^-(\phi, \phi_s)] - [d\sigma^+(\phi, \phi_s + \pi) - d\sigma^-(\phi, \phi_s + \pi)]$$

$$A_{UT}^I(\phi, \phi_s) \propto \text{Im} \left( F_2 \mathcal{H} - F_1 \mathcal{E} \right) \sin(\phi - \phi_s) \cos \phi$$

$$+ \text{Im} \left( F_2 \tilde{\mathcal{H}} - (F_1 + \xi F_2) \tilde{\mathcal{E}} \right) \cos(\phi - \phi_s) \sin \phi$$
**DVCS Transverse Target Spin Asymmetry \( A_{UT}(\phi, \phi_S) \)**

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\[
A_{UT}^I(\phi, \phi_s) \propto [d\sigma^+(\phi, \phi_s) - d\sigma^-(\phi, \phi_s)]^+ + [d\sigma^+(\phi, \phi_s + \pi) - d\sigma^-(\phi, \phi_s + \pi)]
\]

\[
A_{UT}^I(\phi, \phi_s) \propto \text{Im} (F_2 \mathcal{H} - F_1 \mathcal{E}) \sin(\phi - \phi_s) \cos \phi \\
+ \text{Im} \left( F_2 \tilde{\mathcal{H}} - (F_1 + \xi F_2) \tilde{\mathcal{E}} \right) \cos(\phi - \phi_s) \sin \phi
\]
DVCS $A_{UT}$ Amplitudes

Model: VGG with variation of $J_u$, while $J_d=0$
DVCS $A_{UT}$ Amplitudes

With a GPD model describing the data, one could in principle extract a constraint on $J_u + k \cdot J_d$

Model: VGG with variation of $J_u$, while $J_d=0$
DVCS azimuthal amplitudes

(A) Beam charge asymmetry: GPD $H$

(B) Beam helicity asymmetry: GPD $H$

(C) Transverse target spin asymmetry: GPD $E$ from proton target

(D) Longitudinal target spin asymmetry: GPD $\tilde{H}$
HERMES 2006-2007: Recoil Detector

- SC Solenoid (1 Tesla)
- Photon Detector
- Scintillating Fiber Tracker
- Silicon Strip Detector
- Target Cell with unpolarized $^1$H or $^2$H

Purpose:
- To tag exclusive events
- Identify recoiling target proton
- Identify particles from background processes

Azimuthal coverage: 76%

$^1$H ($^2$H): factor of 1.6 (0.5) more than 1996-2005
HERMES 2006-2007: Recoil Detector

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Beam

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$^1$H ($^2$H): factor of 1.6 (0.5)
more than 1996-2005

Azimuthal coverage: 76%
DVCS and the Recoil

- **Missing \( \phi \):** \( \Delta \phi = \phi_{\text{meas}} - \phi_{\text{calc}} \)
- **Missing \( p \):** \( \Delta p = p_{\text{meas}} - p_{\text{calc}} \)

**Missing Mass (\( \approx M^2_P \)):**

\[
M^2_X = (p + p_{\gamma^*} - p_\gamma)^2
\]

**Hermes 2007 data**

- Traditional DVCS analysis
  - \( E_\gamma > 5 \text{ GeV} \)
  - \(|\Delta p| < 1 \text{ GeV/c} \)
  - \(|\Delta p| > 1 \text{ GeV/c} \)
Separation of Resonant and Elastic States with the Recoil

**DVCS / Bethe Heitler**

- **Elastic:**
  - $ep \rightarrow ep\gamma$

- **Resonant ('associated'):**
  - $ep \rightarrow e\Delta^+\gamma$
  - $\Delta^+ \rightarrow \{ n\pi^+, 1/3 \}$
  - $p\pi^0, 2/3$
  - 12% of signal

- Presence of $\pi^0 \Rightarrow$ proton fails coplanarity cut
  - Select elastic:
    - $|\Delta\phi| < 0.1 \text{ rad}$
    - $|p_T^{\text{calc}}|/|p_T^{\text{meas}}| = 0.5 \div 1.5$
  - Select resonant:
    - $|\Delta\phi| > 0.35 \text{ rad}$

**Hermes 2007 data**

- Recoil proton in acceptance with Coplanarity cut turned around
- Counts

$M_x^2 [(GeV/c)^2]$
Summary and Outlook: DVCS at HERMES

HERMES 1996-2005

- Target spin asymmetry on transversely polarized H published in 2008
- BSA and BCA on H, D and nuclear targets to be published in 2009
- Target spin asymmetries on longitudinally polarized H and D early 2010

HERMES 2006-2007

- Recoil detector allows separation of resonant and elastic contributions
- Resonant asymmetry unknown so far
- Allows refinement of pre-Recoil data

HERMES provides complete set of DVCS azimuthal asymmetries as input to global GPD fits
- Limited only by statistics and acceptance