Latest DVCS results from HERMES

Sergey Yaschenko
DESY Zeuthen

on behalf of the HERMES collaboration

EDS-09 CERN, July 1, 2009
Outline

Physics motivation
- DVCS as a tool to access GPDs

HERMES experiment

Recent results on DVCS from HERMES
- Combined analysis of beam-helicity and beam-charge asymmetries on proton and deuteron
- Transverse target polarization asymmetry
- Nuclear-mass dependence of beam-helicity and beam-charge asymmetries

Exclusivity at HERMES: Recoil detector

Summary and outlook
Access to Generalized Parton Distributions (GPDs) via Deeply Virtual Compton Scattering (DVCS)

Cleanest way to access GPDs: DVCS

- **DVCS and Bethe-Heitler**: the same initial and final state
- **Bethe-Heitler dominates at HERMES kinematics**
- **GPDs accessible through cross-section differences and azimuthal asymmetries via interference term**
Generalized Parton Distributions (GPDs)

- **GPDs → PDFs**
  \[ H_q(x,0,0) = q(x) \]
  \[ \tilde{H}_q(x,0,0) = \Delta q(x) \]

- **GPDs → FFs**
  \[ \int_{-1}^{1} dx \, H_q(x,\xi,t) = F_1^q(t) \]
  \[ \int_{-1}^{1} dx \, E_q(x,\xi,t) = F_2^q(t) \]

- \( H_q, E_q \) unpolarized GPDs
- \( \tilde{H}_q, \tilde{E}_q \) polarized GPDs
- \( H_q, \tilde{H}_q \) conserve nucleon helicity
- \( E_q, \tilde{E}_q \) flip nucleon helicity

- \( x \) average parton longitudinal momentum fraction
- \( \xi \) fraction of the longitudinal momentum transfer
- \( t \) squared 4-momentum transfer to the nucleon
Azimuthal asymmetries

Cross section

\[
\sigma_{LU}(\phi; P_B, C_B) = \sigma_{UU}[1 + P_B A_{LU}^{DVCS} + C_B P_B A_{LU}^I + C_B A_C]
\]

Beam-helicity asymmetry

\[
A_{LU}^{DVCS}(\phi) = \frac{\left(\sigma^{+\to} - \sigma^{-\to}\right) - \left(\sigma^{\to\to} - \sigma^{-\to}\right)}{\left(\sigma^{+\to} + \sigma^{-\to}\right) + \left(\sigma^{\to\to} + \sigma^{-\to}\right)} = \frac{1}{D(\phi)} \frac{x_B^2 t P_1(\phi) P_2(\phi)}{Q^2} s_{1}^{DVCS} \sin(\phi)
\]

\[
A_{LU}^I(\phi) = \frac{\left(\sigma^{+\to} + \sigma^{-\to}\right) - \left(\sigma^{\to\to} + \sigma^{-\to}\right)}{\left(\sigma^{+\to} + \sigma^{-\to}\right) + \left(\sigma^{\to\to} + \sigma^{-\to}\right)} = -\frac{1}{D(\phi)} \frac{x_B^2}{Q^2} \sum_{n=1}^{2} s_n^I \sin(n\phi)
\]

Beam-charge asymmetry

\[
A_C(\phi) = \frac{\left(\sigma^{+\to} + \sigma^{++\to}\right) - \left(\sigma^{\to\to} + \sigma^{-\to}\right)}{\left(\sigma^{+\to} + \sigma^{++\to}\right) + \left(\sigma^{\to\to} + \sigma^{-\to}\right)} = -\frac{1}{D(\phi)} \frac{x_B^2}{y} \sum_{n=0}^{3} c_n^I \cos(n\phi)
\]

Azimuthal angle dependence in the denominator

\[
D(\phi) = \frac{\sum_{n=0}^{2} c_n^{BH} \cos(n\phi)}{(1 + \varepsilon^2)^2} + \frac{x_B^2 t P_1(\phi) P_2(\phi)}{Q^2} \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi)
\]

S. Yaschenko

Latest DVCS results from HERMES
Connection of asymmetry amplitudes to GPDs

Connections of Fourier coefficients to GPDs (leading contributions)

\[
c_1^I \propto \sqrt{-t} \frac{Q}{O} \Re \left[ F_1 \mathcal{H} + \tilde{\xi} (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right] \propto -\frac{Q}{\sqrt{-t}} c_0^I
\]

\[
s_1^I \propto \sqrt{-t} \frac{Q}{O} \Im \left[ F_1 \mathcal{H} + \tilde{\xi} (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right]
\]

Extraction of effective asymmetry amplitudes

\[
A_{LU}^{DVCS} (\phi) = \sum_{n=1}^{2} A_{LU,DVCS}^{\sin(n\phi)} \sin(n\phi) + \sum_{n=0}^{1} A_{LU,DVCS}^{\cos(n\phi)} \cos(n\phi)
\]

\[
A_{LU}^I (\phi) = \sum_{n=1}^{2} A_{LU,I}^{\sin(n\phi)} \sin(n\phi) + \sum_{n=0}^{1} A_{LU,I}^{\cos(n\phi)} \cos(n\phi)
\]

\[
A_{C} (\phi) = \sum_{n=0}^{3} A_{C}^{\cos(n\phi)} \cos(n\phi) + A_{C}^{\sin(\phi)}
\]

Combined analysis allows separation of DVCS and interference terms

Comparison with theoretical model (Vanderhaeghen, Guichon, Guidal) [Phys. Rev. D 60 (1999) 094017]
Gas targets:
- Longitudinally polarized H, D
- Unpolarized H, D, $^4$He, N, Ne, Kr, Xe
- Transversely polarized H

Beam:
- Longitudinally polarized $e^+$ and $e^-$ with both helicities
- Energy 27.6 GeV

S. Yaschenko

Latest DVCS results from HERMES
Event selection, uncertainties and corrections

Kinematic requirements

\[ 0.03 < x_B < 0.35 \]
\[ 1 \text{ GeV}^2 < Q^2 < 10 \text{ GeV}^2 \]
\[ -t < 0.7 \text{ GeV}^2 \]
\[ E_\gamma > 5 \text{ GeV} \]

- Identification by missing mass technique \((ep \rightarrow e'\gamma X)\)

- Semi-inclusive corrected as dilutions for charge dependent asymmetries. For pure DVCS term asymmetry extracted from \(\pi^0 (z_\pi > 0.8)\) data

- Associated Bethe-Heitler \(ep \rightarrow e'\Delta^+\gamma \sim 12\%\) stays part of the signal
Results on proton: beam-charge asymmetry amplitudes

\[ \propto - A_C^{\cos \phi} \]

\[ \propto \text{Re}[F_1 H] \]

\[ \leftrightarrow \text{higher twist} \]

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

\[ \leftrightarrow \text{Resonance fraction} \]

\[ e^+ p \rightarrow e^+ p + \gamma \]

The VGG variant with the D-term is disfavored by the beam charge asymmetry

S. Yaschenko

Latest DVCS results from HERMES
Results on proton: beam-helicity asymmetry amplitudes (interference term)

\[ A_{LU,I} = \cos \theta \]
\[ A_{LU,I} = \sin \theta \]
\[ A_{LU,I} = \sin 2\theta \]

\[ \text{Res. frac} \]

\[ \propto \text{Im}[F_1H] \]

Higher twist

Resonance fraction
\[ ep \rightarrow e\Delta^+\gamma \]

\[ \text{VGG bands obtained by varying input parameters } b_{val} \text{ and } b_{sea} \]
\[ \text{VGG model predictions overestimate the size of asymmetry} \]
Results on proton: 
beam-helicity asymmetry amplitudes (DVCS term)

\[ \propto \left[ H H^* + \bar{H} \bar{H}^* \right] \]

Resonance fraction
\[ ep \rightarrow e\Delta^+ \gamma \]
Comparison to deuteron data (beam-charge asymmetry)

Proton (black) and Deuteron (red) data are compatible for all leading amplitudes
Transverse target polarization asymmetry

Results on transverse target polarization asymmetry are published [A. Airapetian et al, JHEP 06 (2008) 066]

Data with transversely polarized hydrogen target (2002-2005)

Access to GPD E - access to the total angular momentum of quarks in the nucleon via Ji relation

\[ J_q = \lim_{t \to 0} \int_{-1}^{1} dx \, x \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right] \]

Model-dependent constraints on \( J_u, J_d \)
Transverse target polarization asymmetry amplitudes

Sensitivity of GPD model predictions to $J_u$ at fixed $J_d=0$

S. Yaschenko

Latest DVCS results from HERMES
DVCS on nuclear targets

- Additional information on GPDs and their modification in nuclear matter
- New opportunity to study the origin of nuclear forces
- Access to 3-D distribution of quarks and gluons in nuclei

Ratio of asymmetries measured on nuclear targets to asymmetries measured with proton target

\[ R_{coh} = 1.8-2.0 \text{ for } A=12-90 \]
Guzey, Strikmann [PRC 68 (2003) 015204]

\[ R_{coh} = 1.0-1.1 \text{ for } A=^{4}\text{He} \]
Liuti, Taneja [PRC 72 (2005) 032201]

\[ R_{coh} = 5/3 \text{ for spin-0, } \frac{1}{2} \]
Kirchner, Müller [EPJ C32 (2003) 347]

\[ A^{\sin \phi}_{LU,nucleus}/A^{\sin \phi}_{LU,proton} \propto A/Z \]
Guzey, Siddikov [JPG 32 (2006) 251]
Coherent/incoherent separation

Nuclear DVCS involves two contributions:
- Coherent process: nuclear target stays intact
- Incoherent process: nuclear target breaks up, photon is emitted by a particular proton or neutron

Separate coherent/incoherent part by cutoff values for $t$

Find upper (lower) $-t$ cut for each target. Asymmetries for coherent (incoherent) production at similar average kinematics
- coherent: $< -t > = 0.018 \text{ GeV}^2$
- incoherent: $< -t > = 0.20 \text{ GeV}^2$

<table>
<thead>
<tr>
<th>Target</th>
<th>$t$ cutoff</th>
<th>estimated %elas. coh.</th>
<th>$\langle t \rangle$ (RMS)</th>
<th>$\langle x_B \rangle$ (RMS)</th>
<th>$\langle Q^2 \rangle$ (RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>$-t &lt; -t_{coh.}$</td>
<td>–</td>
<td>-0.018(0.008)</td>
<td>0.070(0.023)</td>
<td>1.81(0.75)</td>
</tr>
<tr>
<td></td>
<td>$-t &gt; -t_{incoh.}$</td>
<td>–</td>
<td>-0.200(0.120)</td>
<td>0.109(0.059)</td>
<td>2.89(1.62)</td>
</tr>
<tr>
<td>Kr</td>
<td>$-t &lt; -t_{coh.}$</td>
<td>70</td>
<td>-0.018(0.015)</td>
<td>0.064(0.023)</td>
<td>1.63(0.68)</td>
</tr>
<tr>
<td></td>
<td>$-t &gt; -t_{incoh.}$</td>
<td>58</td>
<td>-0.200(0.125)</td>
<td>0.108(0.058)</td>
<td>2.84(1.61)</td>
</tr>
<tr>
<td>Xenon</td>
<td>$-t &lt; -t_{coh.}$</td>
<td>66</td>
<td>-0.018(0.017)</td>
<td>0.062(0.023)</td>
<td>1.60(0.66)</td>
</tr>
<tr>
<td></td>
<td>$-t &gt; -t_{incoh.}$</td>
<td>56</td>
<td>-0.200(0.126)</td>
<td>0.107(0.058)</td>
<td>2.86(1.63)</td>
</tr>
</tbody>
</table>
Beam-charge asymmetry amplitudes (t dependence)

\[ A_C \cos \phi \]

\[ e^{\pm} p \rightarrow e^{\pm} \gamma X \]

\[ e^{\pm} Kr \rightarrow e^{\pm} \gamma X \]

\[ e^{\pm} Xe \rightarrow e^{\pm} \gamma X \]

Resonance %

based on LEPTON with HERMES tuned JETSET
Beam-charge asymmetry amplitudes (A dependence)

Coherent enriched
(accep. & smearing → sys. error,
coherent fraction ~ 65%)

\[ \langle -t \rangle = 0.018 \text{ GeV}^2, \langle x_B \rangle = 0.065, \langle Q^2 \rangle = 1.70 \text{ GeV}^2 \]

Incoherent enriched
(accep. & smearing → sys. error,
elastic incoherent fraction ~ 60%)

\[ \langle -t \rangle = 0.20 \text{ GeV}^2, \langle x_B \rangle = 0.11, \langle Q^2 \rangle = 2.85 \text{ GeV}^2 \]
Beam-helicity asymmetry amplitudes (t dependence)

\[ H, Kr, Xe: \quad A_{LU}^I(\phi) = \frac{(\sigma^{+\to} + \sigma^{-\to}) - (\sigma^{+\to} + \sigma^{-\to})}{(\sigma^{+\to} + \sigma^{-\to}) + (\sigma^{+\to} + \sigma^{-\to})} \]

\[ 4 \text{He}, N, Ne: \quad A_{LU}^I(\phi) = \frac{\sigma^{+\to} - \sigma^{-\to}}{\sigma^{+\to} + \sigma^{-\to}} \]
Beam-helicity asymmetry amplitudes ($A$ dependence)

- **Coherent enriched**
  
  (accep. & smearing $\rightarrow$ sys. error, coherent fraction $\sim$ 65%, except $^3$He $\sim$ 30%)

  $\langle t \rangle = 0.018 \text{ GeV}^2, \langle x_B \rangle = 0.065, \langle Q^2 \rangle = 1.70 \text{ GeV}^2$

- **Incoherent enriched**
  
  (accep. & smearing $\rightarrow$ sys. error, elastic incoherent fraction $\sim$ 60%)

  $\langle t \rangle = 0.20 \text{ GeV}^2, \langle x_B \rangle = 0.11, \langle Q^2 \rangle = 2.85 \text{ GeV}^2$
Ratio of leading beam-helicity asymmetry amplitudes

Coherent enriched
(accep. & smearing \rightarrow sys. error,
coherent fraction \sim 65\%, except $^4$He\sim 30%,
average value: $0.91 \pm 0.19$

Incoherent enriched
(accep. & smearing \rightarrow sys. error,
elastic incoherent fraction \sim 60%)
average value: $0.93 \pm 0.23$

The results do not support models which predict an enhancement of nuclear asymmetries
Data contradict the predicted strong $A$-dependence of the asymmetries resulting from mesonic degrees of freedom in the nuclei
Unpolarized hydrogen target: 38 Mio DIS (41.000 DVCS)
Unpolarized deuterium target: 10 Mio DIS (7.500 DVCS)
Two beam helicities, electron and positron beams
DVCS event selection with the Recoil detector

Missing azimuthal angle versus missing momentum

Hermes 2007 data

Missing mass reconstructed using measured lepton and photon

Hermes 2007 data

Traditional DVCS analysis
$(E_\gamma > 5 \text{ GeV})$

|$\Delta p| < 1 \text{ GeV/c}$

|$\Delta p| > 1 \text{ GeV/c}$
**Summary and outlook**

HERMES produced several interesting results on DVCS which allow to constrain GPD models:

- Beam-charge and beam-helicity asymmetries on proton and deuteron: constraints on GPD $H$
- Transverse target polarization asymmetry: constraints on GPD $E$, model-dependent constraints on $J_u$, $J_d$
- No nuclear-mass dependence of asymmetry amplitudes is observed on nuclear targets: constraints on nuclear GPD models
- Longitudinal target polarization asymmetry: access to GPD $\tilde{H}$

In the 2006/2007 high-statistics data the associated Bethe-Heitler process can be separated using the Recoil Detector information

Refined analysis of data collected before the Recoil detector installation can be performed
Backup slides
Acceptance, bin-width, smearing and misalignment effects

- The difference between “model-generated” and in the HERMES acceptance reconstructed MC amplitudes is taken as systematic uncertainty

S. Yaschenko

Latest DVCS results from HERMES
Proton (black) and Deuteron (red) data are compatible for all leading amplitudes.
Azimuthal dependences

\[
\frac{d^4 \sigma}{dQ^2 dx_B dt d\phi} = \frac{y^2 x_B}{32(2\pi)^4 Q^4 \sqrt{1 + \frac{4M^2 x_B^2}{Q^2}}} \left( |T_{DVCS}|^2 + |T_{BH}|^2 + I \right)
\]

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

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

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