DVCS and Exclusive Processes at Hermes

Caroline Riedl

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Outline

- Motivation
- GPDs and DVCS Azimuthal Asymmetries
- DVCS Measurements at Hermes
- The Hermes Recoil Detector
- Summarizing Overview
The Composition of the Nucleon’s Spin

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g \]

- \( \Delta \Sigma = 1/3 \) from DIS and SIDIS
  - \( \Delta \Sigma = 0.330 \pm 0.011 \) (theo) \( \pm 0.025 \) (exp) \( \pm 0.028 \) (evol)

- \( \Delta G \): first indication from DIS and pp \( \rightarrow \) small

- \( L_q \rightarrow ? \rightarrow \text{Ji’s sum-rule!} \) \( \leftarrow \text{Generalized Parton Distributions} \)
  - **Ji’s sum rule**: Ji, PRL 78 (1997) 610

\[ J_{q,g} = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \ x [H_{q,g}(x, \xi, t) + E_{q,g}(x, \xi, t)] \]

- \( L_g \rightarrow ? \) might be accessible at higher energies than Hermes via GPDs
GPDs: the clever parameterization of the nucleon

PDFs: $H^q(x, 0, 0) = q(x), \tilde{H}^q(x, 0, 0) = \Delta q(x)$ forward limit

Form Factors: $\int dx \ [\text{GPD}] = f(t)$, independent of $\xi$

$\Rightarrow$ GPDs: simultaneous description of transverse position (FF) and momentum distribution (PDF): “Nucleon Tomography”

Sum rule for $J$ of quarks/gluons! Need $H$ and $E$ for $t \to 0$

Recent theoretical reviews:

DVCS: the prime process to access GPDs

- $d\sigma \propto |T|^2 = |T_{DVCS}|^2 + |T_{BH}|^2 + I$
- **Interference:** $I = T_{DVCS} T_{BH}^* + T_{DVCS}^* T_{BH}$
- **Hermes kinematics:** $|T_{DVCS}|^2 < |T_{BH}|^2$
- $I \propto \pm (c_0 + \sum_n [c_n \cos(n\phi) + s_n \sin(n\phi)])$
  - $c_n =$ Lin. Comb. $(UU), (UT), (LL), (LT)$
  - $s_n =$ Lin. Comb. $(LU), (UL), (UT), (LT)$

Project out sin- and cos-moments by different:
- beam charges
- beam helicities
- target polarizations (long. and trans.)

⇒ Azimuthal asymmetries
⇒ Linear combinations of GPDs
The Hermes forward spectrometer
The powerful DVCS data pool of Hermes


- 2 beam charges (1,2,3), 2 beam helicities (1,2,3)
- **longitudinally** (1) and **transversely** (2) polarized target
- unpolarized nuclear targets (1,2)
- Recoil Detector (3)
Finding exclusive events

Classic technique at Hermes: access to exclusivity via missing mass

\[ M_x^2 = (P_e + P_P - (P_{e'} + P_\gamma))^2 \]

2006/07: recoiling proton detected \( \Rightarrow \) all reaction partners measured!

\[ X = p \]
\[ X = \Delta^+ \rightarrow n\pi^0 \]
\[ X = \pi^0 + \ldots \]
The gallery of DVCS azimuthal asymmetries

1. Beam Charge Asymmetry $A_C(\phi)$

$$d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \text{Re}(F_1\mathcal{H})\cos \phi$$

2. Beam Spin Asymmetry $A_{LU}(\phi)$

$$d\sigma(\tilde{e}, \phi) - d\sigma(\tilde{e}, \phi) \propto \text{Im}(F_1\mathcal{H})\sin \phi$$

3. Longitudinal Target Spin Asymmetry $A_{UL}(\phi)$

$$d\sigma(\vec{P}, \phi) - d\sigma(\vec{P}, \phi) \propto \text{Im}(F_1\tilde{\mathcal{H}})\sin \phi$$

4. Transverse Target Spin Asymmetry $A_{UT}(\phi, \phi_s)$

$$d\sigma(\phi, \phi_s) - d\sigma(\phi, \phi_s + \pi) \propto \text{Im}(F_2\mathcal{H} - F_1\mathcal{E})\sin(\phi - \phi_s)\cos \phi + \text{Im}(F_2\tilde{\mathcal{H}} - F_1\xi\tilde{\mathcal{E}})\cos(\phi - \phi_s)\sin \phi$$

$F_1, F_2$: Pauli, Dirac Form Factors; $\mathcal{H}, \tilde{\mathcal{H}}, \mathcal{E}, \tilde{\mathcal{E}}$: Compton Form Factors (convolutions of hard scattering amplitude and corresponding twist-2 GPD)
1. Beam Charge Asymmetry (BCA) versus $\phi$

$$A_C(\phi) = \frac{d\sigma(e^+, \phi) - d\sigma(e^-, \phi)}{d\sigma(e^+, \phi) + d\sigma(e^-, \phi)} \propto \text{Re}(F_1 H) \cos \phi$$

**HERMES** $e^\pm p \rightarrow e^\pm \gamma X$ ($M_x < 1.7$ GeV)

$P_1 = -0.011 \pm 0.019$
$P_2 = 0.060 \pm 0.027$
$P_3 = 0.016 \pm 0.026$
$P_4 = 0.034 \pm 0.027$

Contributions for ed → eXγ:
- coherent (X=d): 20%
- incoherent (X=pn): 60%
- associated (X=Δ): 15%


Factor of ≈ 20 more e− and factor of ≈ 7 more e+ data on tape!
2. Beam Spin Asymmetry (BSA)

\[ A_{LU}(\phi) = \frac{1}{|P_B|} \cdot \frac{d\sigma(\overrightarrow{e}, \phi) - d\sigma(\overleftarrow{e}, \phi)}{d\sigma(\overrightarrow{e}, \phi) + d\sigma(\overleftarrow{e}, \phi)} \propto \text{Im}(F_1H) \sin \phi \]

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

**HERMES PREL. 2000** (refined)

- \( P1 + P2 \sin \phi + P3 \sin 2\phi \)

\[ \langle -t \rangle = 0.18 \text{ GeV}^2, \quad <x_B> = 0.12, \quad <Q^2> = 2.5 \text{ GeV}^2 \]

\[ P1 = -0.04 \pm 0.02 \text{ (stat)} \]
\[ P2 = -0.18 \pm 0.03 \text{ (stat)} \]
\[ P3 = 0.00 \pm 0.03 \text{ (stat)} \]

**HERMES PRELIMINARY 2000** (refined analysis)

\[ \text{\overrightarrow{e}^+ p \rightarrow \text{e}^+ \gamma X} \]

\[ A_{LU}^{\sin \phi} \quad |_{M_x < 1.7 \text{ GeV}} = -0.18 \pm 0.03 \text{ (stat)} \pm 0.03 \text{ (sys)} \]
\[ \langle -t \rangle = 0.18 \text{ GeV}^2, \quad <x_B> = 0.12, \quad <Q^2> = 2.5 \text{ GeV}^2 \]

**Hermes publication:** PRL **87** (2001) 182001

**Factor of \( \approx 9 \) more data on tape**
3. Longitudinal Target Spin Asymmetry (LTSA)

\[ A_{UL}(\phi) = \frac{1}{\langle |P_T| \rangle} \cdot \frac{d\sigma(\bar{P}, \phi) - d\sigma(P, \phi)}{d\sigma(\bar{P}, \phi) + d\sigma(P, \phi)} \propto \text{Im}(F_1 \tilde{H}) \sin \phi \]

HERMES PRELIMINARY
\[ e^+ p/d \rightarrow e^+ \gamma X \ (M_X < 1.7 \text{ GeV}) \]
(proton deuter \( \sin \phi \))

GPD model: see reference @ BCA

Plots: Full statistics
4. Transverse Target Spin Asymmetry (TTSA)

\[ A_{UT}(\phi, \phi_s) = \frac{1}{\langle |P_T| \rangle} \cdot \frac{d\sigma(\phi, \phi_s) - d\sigma(\phi, \phi_s + \pi)}{d\sigma(\phi, \phi_s) + d\sigma(\phi, \phi_s + \pi)} \]

sensitive to \( J_u \):
\[ \text{Im}(F_2 \mathcal{H} - F_1 \mathcal{E}) \cdot \sin(\phi - \phi_s) \cos\phi + \]

NOT sensitive to \( J_u \):
\[ \text{Im}(F_2 \tilde{\mathcal{H}} - F_1 \tilde{\mathcal{E}}) \cdot \cos(\phi - \phi_s) \sin\phi \]

Sensitivity on \( J_u \): hep-ph/0506264, assuming \( J_d = 0 \)

Factor of 1 more data
First (Model-Dependent) Constraint on $J_u + k \cdot J_d$

\[
\chi^2(J_u, J_d) = \frac{\left( A_{UT} \sin(\phi - \phi_s) \cos \phi \right)_\text{exp} - \left( A_{UT} \sin(\phi - \phi_s) \cos \phi \right)_\text{VGG}(J_u, J_d) }{\delta A^2 + \delta A^2_{\text{sys}}} ^ 2
\]

- $J_u$ and $J_d$ free params in GPD model (VGG)
- 1-sigma constraint on $J_u$ vs. $J_d$:
  \[
  \chi^2(J_u, J_d) \leq \chi^2_{\text{min}} + 1 \]
  (brown band)
2b. DVCS on nuclear targets

- How does the nuclear environment modify parton-parton correlations?
- Hermes nuclear targets: \(^2\text{H}, ^4\text{He}, ^{14}\text{N}, ^{20}\text{Ne}, ^{82–86}\text{Kr}, ^{129–134}\text{Xe}\)
2b. DVCS on nuclear targets

- How does the nuclear environment modify parton-parton correlations?
- Hermes nuclear targets: $^2H$, $^4He$, $^{14}N$, $^{20}Ne$, $^{82-86}Kr$, $^{129-134}Xe$
- Nuclear BSA: clear $\sin \phi$ amplitude in the exclusive region

Integrated kinematics:
Neon: $-0.22 \pm 0.03 \pm 0.03$
proton: $-0.18 \pm 0.03 \pm 0.03$
2b. DVCS on nuclear targets

- How does the nuclear environment modify parton-parton correlations?
- **Hermes nuclear targets:** $^2\text{H}$, $^4\text{He}$, $^{14}\text{N}$, $^{20}\text{Ne}$, $^{82-86}\text{Kr}$, $^{129-134}\text{Xe}$

![Graph showing the nuclear-to-hydrogen ratio of BSA sin $\phi$ amplitudes]

Nuclear-to-hydrogen ratio of BSA sin $\phi$ amplitudes:

(coherent)

$$(A/H) = 1.58 \pm 0.26$$

(incoherent):

$(A/H)$ consistent with 1

$\sqrt{\text{GPD model prediction}}$

PRC68 (2003) 015204

Factor of $\approx 2/1$ more data on tape for Xenon/Krypton
Recoil Detector installation: December 2005

The diagram illustrates the layout of the Recoil Detector with various components labeled:

- Target Cell
- Steel Plate
- Magnetic Field
- Drift Chambers
- Trigger Hodoscope H1
- Preshower (H2)
- Calorimeter
- Luminosity Monitor
- RICH
- Silicon Chambers
- Electronics

C. Riedl (DESY)
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The Hermes Recoil Detector

- **Superconducting Solenoid** (1 Tesla)
- **Photon Detector**
  - 3 layers of Tungsten/Scintillator
  - $\pi^0$ background suppression
- **Scintillating Fiber Tracker**
  - 2 Barrels
  - Each 2 parallel- & 2 stereo-layers
  - Stereo angle: $10^\circ$
  - **Momentum reconstruction & PID**
- **Silicon Strip Detector**
  - 2 Layers
  - 16 double-sided sensors
  - $(10\text{cm} \times 10\text{cm})$ active area
  - Inside accelerator vacuum
  - **Momentum reconstruction & PID**
- **Target Cell** with unpol. $H_2$ or $D_2$
The Recoil Road to genuine exclusivity at Hermes

 Silicon & Fiber Tracker:
\[ p_p \in [135, 1200] \text{MeV}/c \]
\[ p/\pi \text{ PID for } p < 700 \text{MeV}/c \]

 Photon Detector:
\[ p/\pi \text{ PID for } p > 650 \text{MeV}/c \]

- Recoiling protons
  - Enhance **signal fraction**
  - Improve \( t \)-resolution
- Background pions and protons
- Photons from \( \pi^0 \rightarrow \gamma\gamma \)

⇒ Reduce **background contributions**:
- **sidis**: 5\% \( \ll \) 1\%
- **associated production**: 11\% \( \downarrow \) 1\%
Recoil: First physics signatures

Silicon Detector

Hermes data

- Energy Deposit Outer Silicon [keV]
- Energy Deposit Inner Silicon [keV]
Recoil: First physics signatures

Silicon Detector
Hermes data

Momentum ($p$) reconstruction:

1. **Low momentum protons:**
   \[ p \text{ by } \Sigma(\text{energy deposits}) \]

2. **Higher momentum protons:**
   \[ p \text{ by Bethe-Bloch (dE/dx)} \]

3. **High momentum particles:**
   \[ p \text{ by bending in B-field, tracks formed by spacepoints in (up to) 2 subdetectors} \]
Recoil: First physics signatures

⇒ $p/\pi$ PID:
Recoil: Proof of Principle

Response of Recoil Silicon Detector for “traditional DVCS candidates” (events with 1 lepton and 1 photon in front spectrometer):

![Graph showing Silicon Detector Hermes data with a cut on $M_x^2$.]
The Recoil Adventure goes on!

- Hera stopped its operation 4 weeks ago, Hermes took last data
- Collected statistics (preliminary) with operational recoil detector:
  - **Electron beam** 2006 (only Fiber Tracker operational):
    - $H_2$: 5k DVCS (3 Mio DIS), $D_2$: 1k DVCS (0.8 Mio DIS)
  - **Positron beam** 2006/07 (all subdetectors fully operational):
    - $H_2$: 42k DVCS (28 Mio DIS), $D_2$: 10k DVCS (7 Mio DIS)
- Analysis of BCA and BSA with recoil data
- Detector understanding in progress
  - Calibration
  - Alignment
  - Noise
  - Tracking
  - ...

⇒ Watch out for first results!
### Summary: Hermes and Exclusive Processes

<table>
<thead>
<tr>
<th>unpolarized</th>
<th>polarized</th>
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<tbody>
<tr>
<td>$H$: BCA, BSA,</td>
<td>$\tilde{H}$: LTSA (TTSA)</td>
</tr>
<tr>
<td>TTSA</td>
<td>$\tilde{E}$: (TTSA)</td>
</tr>
<tr>
<td>$E$: TTSA</td>
<td>x-section</td>
</tr>
<tr>
<td>$J^P = 1^- \text{ mesons}$</td>
<td>$J^P = 0^- \text{ mesons}$</td>
</tr>
<tr>
<td>photon: $J^P = 1^-$ (DVCS)</td>
<td>see talk</td>
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<td>J. Dreschler</td>
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- GPD models agree in general with measurements
- First model-dependent extraction of $J_u + k \cdot J_d$ possible
- Most published DVCS results await a significant statistics upgrade: BCA (factor 20 / 7 more), BSA (factor 9), TTSA (factor 1)
- Recoil-data is being prepared for physics analysis
  $\Rightarrow$ exploit direct exclusivity: no mass is missing anymore!
- Once background contribution is measured: refined analysis of pre-recoil DVCS and DVMP data

![Diagram](image.png)