Deeply Virtual Compton Scattering at HERMES – an Overview

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CEA-Saclay
March 27, 2013
Outline: DVCS @ HERMES

- Setting the scene
- Results on the proton target
- Results using recoil-proton detection
- Results on targets heavier than the proton
Nucleon Tomography

**Correlation between spin and transverse momentum?**

**Correlation between longitudinal momentum and transverse position?**

**Transverse Momentum dependent PDFs**

\[ f(x, k_{\perp}) \]

Generalized Parton Distributions

\[ H(x, b_{\perp}) \]

\[ \leftrightarrow \text{FT} \leftrightarrow H(x, \xi, t) \]

**semi-inclusive measurements**

**inclusive measurements**

**exclusive measurements**

**k_{\perp}-integration**

**Courtesey A. Bacchetta (Università di Pavia)**
DVCS as Laboratory for Probing Hadrons

1. Access to Generalized Parton Distributions
   - "Nucleon Tomography"
   - Global analysis

2. Access to total angular momentum of quarks through Ji sum rule
   \[ J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \ x \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right] \]
   - Ji, PRL 78 (1997) 610-

3. DVCS on hadrons other than the nucleon
   Spin-1: tensor and coherent signatures?
   How does the nuclear environment modify the DVCS amplitude?
Hard Exclusive Reactions and GPDs

4 chiral-even quark GPDs at leading twist

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<th>Spin-½</th>
<th>flips nucleon helicity</th>
<th>conserves nucleon helicity</th>
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<tr>
<td>does not depend on quark helicity</td>
<td>E</td>
<td>H</td>
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<tr>
<td>depends on quark helicity</td>
<td>Ẽ</td>
<td>H̃</td>
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- x, ξ: longitudinal momentum fractions of probed quark
- t: squared 4-momentum transfer to target
- DVCS: Deeply Virtual Compton Scattering = electroproduction of a real photon
Deeply Virtual Compton Scattering

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

**DVCS-BH interference term**

**average HERMES kinematics**

- \( Q^2 = 2 \text{ GeV}^2 \)
- \( x_B = 0.1 \)

Harmonic Analysis

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

\[ |\tau_{DVCS}|^2 = \frac{1}{Q^2} \left\{ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + \lambda s_1^{DVCS} \sin \phi \right\} \]

\[ I = \frac{-\epsilon_{\mu} K_1}{P_1(\phi) P_2(\phi)} \left\{ \sum_{n=0}^{3} c_n^{LU} \cos(n\phi) + \sum_{n=1}^{2} \lambda s_n^{LU} \sin(n\phi) \right\} \]

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

Beam-helicity asymmetries

Beam-charge asymmetry

\[ A_C(\phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \]

Approach at HERMES:

\[ s_1^{LV} \text{ and } s_1^{DVCS} \text{ can be disentangled} \]

Need 2 beam charges!

Charge-average \( A_{LU}^{DVCS}(\phi) \):

\[ \frac{(d\sigma^{+\to} - d\sigma^{+\to}) + (d\sigma^{-\to} - d\sigma^{-\to})}{(d\sigma^{+\to} + d\sigma^{+\to}) + (d\sigma^{-\to} + d\sigma^{-\to})} \]

Charge-difference \( A_{LU}^{I}(\phi) \):

\[ \frac{(d\sigma^{+\to} - d\sigma^{-\to}) - (d\sigma^{-\to} - d\sigma^{-\to})}{(d\sigma^{+\to} + d\sigma^{+\to}) + (d\sigma^{-\to} + d\sigma^{-\to})} \]

Old approach at HERMES

and CLAS: single-charge \( A_{LU} \)

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

no separate access to \( s_1^{LV} \) and \( s_1^{DVCS} \)
Azimuthal Asymmetries and GPDs

Single-charge beam-helicity asymmetry

\( \mathcal{A}_{LU}(\phi) \equiv \frac{d\sigma^\to - d\sigma^\leftarrow}{d\sigma^\to + d\sigma^\leftarrow} \)

Charge-average asymmetry

Charge-difference asymmetry

Beam-helicity asymmetries with 2 beam charges

Beam-charge asymmetry

Charge-average

Charge-difference

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

\( s_1^{DVCS} \) and \( s_1^I \) can be disentangled

Compton Form Factors (CFFs)

\[
\mathcal{F}(\xi, t) = \sum_{q} \int_{-1}^{1} dx \ C_q^{\pm}(\xi, x) F^q(x, \xi, t)
\]

twist-2 GPD

Measure asymmetry

Extract its azimuthal moments (extended Maximum Likelihood Fit)

Those azimuthal asymmetry amplitudes are related to certain linear or bi-linear combinations of CFFs.

☛ Measure asymmetry

☛ Extract its azimuthal moments (extended Maximum Likelihood Fit)

☛ Those azimuthal asymmetry amplitudes are related to certain linear or bi-linear combinations of CFFs.
HERMES DVCS Results

HERA @ DESY retired 30.6.2007

Gas target internal to lepton ring

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

e+ / e- beam 27.6 GeV

Hermes

1995-2007
Results on the proton target

- Proton target with **longitudinal** (50 /pb) & **transverse** polarization (150 /pb); unpolarized (1200 /pb, thereof 670 /pb with fully operational recoil detector)

- Deuteron target with **longitudinal** polarization (200 /pb); unpolarized (800 /pb)

- Nuclear Targets: He, N, Ne, Kr, Xe (300 /pb)
### DVCS Amplitudes

(A) Beam-charge asymmetry:
GPD H


(B) Beam-helicity asymmetry:
GPD H


(C) Transverse target-spin asymmetry:
GPD E

[JHEP 06 (2008) 066]

(D) Double-Spin (LT) asymmetry: GPD E


(E) Longitudinal target-spin asymmetry:
GPD H~


(F) Double-spin (LL) asymmetry: GPD H~


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**HERMES DVCS**

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<th>Amplitude</th>
<th>Hydrogen</th>
<th>Deuterium</th>
<th>Hydrogen Pure</th>
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<td>$A_{C}^{\cos(0\theta)}$</td>
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“Traditional” DVCS Analysis

“exclusive region” in (missing mass)$^2$

unresolved sample

- No other charged tracks reconstructed
- No other untracked clusters in the calorimeter

Missing-mass technique

\[ M_X^2 = (k + p - k' - q')^2 \]

ep $\rightarrow$ eX$\gamma$ sample

× Unresolved for associated production
✓ Semi-inclusive neutral pion production corrected for

criedl@illinois.edu - HERMES DVCS Results
Beam-Charge Asymmetry

Global fit including data from JLab, HERMES and HERA colliders (dashed excludes JLab Hall A cross section)

[arXiv:0904.0458]

[arxiv:1012.3776]

Associated fraction ep→eΔ⁺γ (from MC simulation)

JHEP 07 (2012) 032
Beam-Helicity Asymmetry

Overall fraction

Assoc. fraction

\[ A_{LU,I} \sin \phi \]

\[ A_{LU,DVCS} \sin \phi \]

\[ A_{LU,I} \sin (2 \phi) \]

-0.4  -0.2  0  0.2  0.4

KM09 (a)  KM09 (b)  GGL11  GPD H

All 1996–2007 proton data

JHEP 07 (2012) 032
2-Dimensional
(-t, Q^2) Binning

beam-helicity asymmetry

1D results also available in
“traditional binning” with 4 bins
(→ global fits)

beam-charge asymmetry

GPD H

All 1996–2007
proton data
Transverse Target-Spin Asymmetry

Model curves:
VGG Regge, no D-term
3 different values for $J_u$ fixed $J_d=0$
Double-Spin (LT) Asymmetry

Charge-difference

2002–2005 transversely polarized proton data

Double-Spin (LT) Asymmetry

Charge-averaged

2002–2005 transversely polarized proton data

Total angular momentum of quarks

\( \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g \)

Nucleon spin

**Ji sum rule for the nucleon**

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

- Ji, PRL 78 (1997) 610-

**Caveat:** Model-dependent constraint on \( J_u + k \cdot J_d \). GPD models are far from describing all available data equally well!!

(A) HERMES: \( ep^\uparrow \rightarrow ep\gamma \): 
\( H-E \) (transversely polarized target)

(B) Hall A: \( \vec{e}^\uparrow n \rightarrow e^- n \gamma \): 
\( E \) dominant for the neutron (unpolarized target)

Longitudinal Target-Spin Asymmetry

target-spin asymmetry

1996/1997 longitudinally polarized proton data

double-spin (LL) asymmetry


VGG Regge
DVCS Amplitudes

(A) Beam-charge asymmetry:
GPD H

\[ \text{JHEP 07 (2012) 032} \]
\[ \text{Nucl. Phys. B 829 (2010) 1–27} \]

(B) Beam-helicity asymmetry:
GPD H

\[ \text{JHEP 07 (2012) 032} \]
\[ \text{– Nucl. Phys. B 829 (2010) 1–27} \]
\[ \text{– JHEP10 (2012) 042} \]

(C) Transverse target-spin asymmetry:
GPD E

\[ \text{JHEP 06 (2008) 066} \]

(D) Double-Spin (LT) asymmetry: GPD E


(E) Longitudinal target-spin asymmetry:
GPD H~

\[ \text{JHEP 06 (2010) 019} \]
\[ \text{– Nucl. Phys. B 842 (2011) 265–298} \]

(F) Double-spin (LL) asymmetry:
GPD H~

\[ \text{JHEP 06 (2010) 019} \]
\[ \text{– Nucl. Phys. B 842 (2011) 265–298} \]
Global analysis of DVCS data

Kresimir Kumericki & Dieter Müller

- Global fit to extract GPD $H$ at cross-over line $\xi=x$. NNLO
- HERMES $A_C$, CLAS $A_{LU}$ and Hall A $x$-section.
- Small-$x$ behavior from HERA collider data.

Desirable: As many observables as possible sensitive to different CFFs

Compton Form Factors

  - Global fit to extract Re($H$) & Im($H$)
  - Hall A $x$-section & CLAS $A_{LU}$

- Michel Guidal arXiv:1011.4195
  - Model-independent fit of Re($CFF$) & Im($CFF$)
  - HERMES: $A_C$, $A_{LU}$, $A_{UT}$, $A_{UL}$, $A_{LL}$
  - CLAS: $A_{LU}$, $A_{UL}$
  - Hall A: $x$-section
Results using recoil-proton detection
The HERMES Recoil Detector

2006/2007 unpolarized proton and deuteron data

Purpose: tagging of exclusive events

SC Solenoid (1 Tesla)

Photon Detector PD

Scintillating Fiber Tracker SFT

Silicon Strip Detector SSD

Target Cell

Beam

x2 x4

300 μm thick

Target Cell

arXiv:1302.6092, submitted to JINST

criedl@illinois.edu - HERMES DVCS Results
Track Reconstruction
with recoil detector

Hermes 2007 data

Recoiling proton candidates
DVCS

azimuthal-angle resolution: 4 mrad
polar-angle resolution: 10 mrad
(for $p>0.5$ GeV)

Momentum reconstruction down to
125 MeV (protons).
Want as low $-t$ as possible!
(corresponds to $-t=0.016$ GeV$^2$)

pions: $\Delta p/p=0.12$
protons
magnetic bending only
energy deposit & bending

criedl@illinois.edu - HERMES DVCS Results
Adding the Recoil Proton

Kinematic event fitting

$$\chi^2_{pen} = \sum_{i=1}^{9} \frac{(r_i^{fit} - r_i^{meas})^2}{\sigma_i^2} + T \cdot \sum_{j=1}^{4} \frac{[f_j(r_1^{fit}, \ldots, r_9^{fit})]^2}{(\sigma_j^{fit})^2}$$

- $f_j$: 4 constraints of 4-momentum conservation & assuming proton mass
- Hypothesis: ep→epy event
  $\Rightarrow$ require: $\chi^2 < 13.7$

Only epγ detection
unresolved sample

- experimental data
- simulation (sum)
- ep→epγ
- ep→eΔ⁺γ
- semi-inclusive

ephy detection
pure sample

- >99.8% ep→epy purity

Unresolved for Δ⁺

~88% ep→epy purity

criedl@illinois.edu - HERMES DVCS Results
Unresolved Reference Sample
Disentangling the effects of recoil-detector acceptance and purification

Loss due to
- lower-mom. threshold
- Φ-gaps of SSD

Deficit due to
- removal of background
- inefficiencies of χ² cut
- recoil-det. inefficiencies

Unresolved sample
(traditional analysis)

Unresolved-reference

Pure sample

Traditional sample plus acceptance function

1000×10\(^{-6}\)×(N/N_{DIS})

M\(_X^2\) [GeV\(^2\)]

M\(_X^2\) [GeV\(^2\)]

M\(_X^2\) [GeV\(^2\)]

experimental data
simulation (sum)
ep→epγ
ep→eΔγγ
semi-inclusive
# Available Statistics

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<tr>
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<th>$P_\ell &gt; 0$</th>
<th>$P_\ell &lt; 0$</th>
<th>total</th>
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<td>integrated luminosity</td>
<td>430 pb$^{-1}$</td>
<td>240 pb$^{-1}$</td>
<td>670 pb$^{-1}$</td>
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<td>DIS events (/10$^6$)</td>
<td>15.8</td>
<td>8.7</td>
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<td>23000</td>
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<td>9200</td>
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<td>$\langle P_\ell \rangle$</td>
<td>0.402</td>
<td>-0.394</td>
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Beam-Helicity Asymmetry with Recoil-Proton Detection

“traditional” analysis

acceptance function

recoil-proton detection & kinematic event fit

GPD H

2006/2007 proton data

single-charge

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criedl@illinois.edu - HERMES DVCS Results
Beam-Helicity Asymmetry with Recoil-Proton Detection

Global fit of world data
JLab, HERMES and HERA,
dashed excludes JLab Hall A cross section

GPD model calculation “VGG Regge”

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Associated Electroproduction of Real Photons

$ep \to e\gamma(\pi N)$ in the $\Delta$-resonance region

- The charged particle of ($\pi N$) reconstructed by the recoil detector.

- Kinematic event fitting under the hypotheses:
  - $ep \to e\gamma\pi^0p$: neutral-pion mass as constraint plus identified $p$ in recoil detector
  - $ep \to e\gamma\pi^+n$: neutron mass as constraint plus identified $\pi^+$ in recoil detector
  - $\Delta^+(1232)$ mass as constraint

- Reject “pure” $ep \to e\gamma$ events

<table>
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<tr>
<th>Kinematic bin</th>
<th>$ep \to e\gamma\pi^0p$ (%)</th>
<th>$ep \to e\gamma p$ (%)</th>
<th>SIDIS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>85.7 ± 1.8</td>
<td>1.1 ± 0.1</td>
<td>13.2 ± 1.9</td>
</tr>
<tr>
<td>Kinematic bin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall</td>
<td>75.6 ± 2.6</td>
<td>0.1 ± 0.1</td>
<td>24.4 ± 3.4</td>
</tr>
</tbody>
</table>

Corrected for variation 5-26% and 9-43%
Beam-Helicity Asymmetry in $e^p \to e^+ e^- \pi^0(\pi^n)$

This result is consistent with the slight increase of the beam-helicity asymmetry amplitude for the pure sample.

Associated process acts as small dilution in the asymmetries for the unresolved sample.

Only existing model prediction for $\sin \phi$ amplitude:
- $\pi^0 p$: $-0.15$
- $\pi^+ n$: $-0.10$


2006/2007 proton data

Preliminary analysis
Results on targets heavier than the proton

- Proton target with longitudinal (50 /pb) & transverse polarization (150 /pb); unpolarized (1200 /pb, thereof 670 /pb with fully operational recoil detector)
- Deuteron target with longitudinal polarization (200 /pb); unpolarized (800 /pb)
- Nuclear Targets: He, N, Ne, Kr, Xe (300 /pb)
Deuteron Target

Spin-1

\[ \mathcal{H}_1, \mathcal{H}_2, \mathcal{H}_3, \mathcal{H}_4, \mathcal{H}_5, \mathcal{\tilde{H}}_1, \mathcal{\tilde{H}}_2, \mathcal{\tilde{H}}_3, \mathcal{\tilde{H}}_4 \]

- 9 chiral-even quark GPDs at leading twist
- \( \mathcal{H}_3, \mathcal{H}_5 \) associated with 5% D-wave component of deuteron wave function

Spin-1/2

<table>
<thead>
<tr>
<th></th>
<th>flips nucleon helicity</th>
<th>conserves nucleon helicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>does not depend on quark helicity</td>
<td>E</td>
<td>H</td>
</tr>
<tr>
<td>depends on quark helicity</td>
<td>( \mathcal{\tilde{E}} )</td>
<td>( \mathcal{\tilde{H}} )</td>
</tr>
</tbody>
</table>

4 chiral-even quark GPDs at leading twist

Longitudinally polarized deuteron

- Vector polarization \( P_z \approx 0.85 \)
- Tensor polarization \( P_{zz} \approx 0.83 \)
- Dedicated data set with \( P_{zz} = -1.656 \) \& \( P_z \approx 0 \)

Spin-1 particle with \( \Lambda = -1, 0, +1 \)

\[
\begin{align*}
P_{zz} &= \frac{n^+ - n^-}{n^+ + n^- + n^0} \\
P_z &= \frac{n^+ - n^-}{n^+ + n^- + n^0}
\end{align*}
\]
Target-Spin Asymmetry on $p$ and $d$

Search for coherent signature

1998–2000 longitudinally polarized deuteron data

coherent

incoherent

DVCS

Bethe-Heitler

Deuteron: probe spin-1 object

Nucleon: probe spin-1/2 object

$GPD H_1 \sim$

Beam-Helicity Asymmetry on $p$ and $d$

Search for tensor signature

1998–2000 longitudinally polarized deuteron data

$H_5$ = tensor structure function in the forward limit

$\text{DVCS } A_{LZZ} \text{ (tensor asymmetry) } \sin \phi$ amplitude:

$0.074 \pm 0.196 \pm 0.022$

$(-t<0.06 \text{ GeV}^2, 40\% \text{ coherent})$


GPDs $H_1, H_5$
Nuclear Data Sets

<table>
<thead>
<tr>
<th>Target</th>
<th>Spin</th>
<th>$L , (\text{pb}^{-1})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>$1/2$</td>
<td>227</td>
</tr>
<tr>
<td>He</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>51</td>
</tr>
<tr>
<td>Ne</td>
<td>0</td>
<td>86</td>
</tr>
<tr>
<td>Kr</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>Xe</td>
<td>0, $1/2$, $3/2$</td>
<td>47</td>
</tr>
</tbody>
</table>

Heavy target data taken at the end of each HERA fill (“high density runs”)

- Separation of coherent-enriched and incoherent-enriched data samples by $t$-cutoff such that $\approx$ same average kinematics for each target.
- Coherent enriched samples: $\approx 65\%$ coherent fraction
- Incoherent enriched samples: $\approx 60\%$ incoherent fraction
DVCS Asymmetries on Nuclei

- Targets with 2 beam charges available. $A_C$ and charge-difference $A_{LU}$ sensitive to DVCS-BH interference term
  - Targets with only one beam charge available. No $A_C$ and single-charge $A_{LU}$ with entangled $s_1$ coefficients

DVCS Nuclear Mass Dependence

**AC^{cos\phi} vs. A**

- Coherent enriched
- Incoherent enriched

**ALU^{sin\phi} vs. A**

- Average \( ALU^A / ALU^H: \)
  - 0.91±0.19
  - 0.93±0.23

**Beam-charge asymmetry**

- How does the nuclear medium modify parton-parton correlations?
- How do the nucleon properties change in the nuclear medium?
- Is there an enhanced ‘generalized EMC effect’, which could be revealed through the rise if \( \tau_{DVCS} \) with \( A \)?

**Beam-helicity asymmetry**

- Normalization to hydrogen \(^1\text{H}\)
Summary: DVCS at HERMES

- Results on the proton, the deuteron and nuclear targets.
- Complete and so far unique set of azimuthal asymmetry amplitudes with respect to beam charge, beam helicity and longitudinal / transverse target polarization.
- Unpolarized data allows access to GPD H; beam charge projects real part of CFF related to H; beam helicity its imaginary part. Polarized data allows access to GPDs H~ and E.
- Heavier targets allow searches for coherent and tensor signatures.
- DVCS at HERMES possible without recoil detector; contamination by associated DVCS can only be separated with full event reconstruction using recoil-detector data.
Backup
The Spin of the Nucleon

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

- quark spin
- gluon spin [very small]
- quark orbital and orbital angular momentum

\[ \Delta \Sigma \approx \frac{1}{3} \]
Dynamic Hologram of the Nucleon

\[ W(x, b_{\perp}, k_{\perp}) \]

Correlation between spin and transverse momentum?

**GPDs:** Generalized Parton Distributions

\[ H(x, b_{\perp}) \]

FT

\[ H(x, \xi, t) \]

\[ \xi = 0, t = 0 \]

**TMDs:** Transverse Momentum dependent PDFs

\[ f(x, k_{\perp}) \]

3D in momentum space

\[ k_{\perp}-\text{integration} \]

PDFs \( q(x) \): Parton Distribution Functions

1D

semi-inclusive measurements

exclusive measurements

Correlation between longitudinal momentum and transverse position?

Wigner phase-space distributions


"mother distributions"

[Meissner, Metz, Schlegel, JHEP 0908:056, 2009]
Nucleon Tomography

Form Factors from elastic scattering

Generalized Parton Distributions

Parton Distribution Functions from inclusive deep-inelastic scattering

Illustrations: Ph. H"agler (TUM)
### Holographic principle in DVCS

- BH reference amplitude magnifies DVCS
- Measure magnitude $A$ and phase $\varphi$ of DVCS amplitude $\tau_{DVCS} = Ae^{i\varphi}$

Belitsky, Müller, hep-ph/0206306
Parameterization of observables in terms of GPDs

**Compton Form Factors:**

- **unpolarized target:**
  \[ F_1 \mathcal{H} + \frac{x_B}{2-x_B} (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \]
  - dominant for the proton
  - Best access

- **longitudinally polarized target:**
  \[ \frac{x_B}{2-x_B} (F_1 + F_2) (\mathcal{H} + \frac{x_B}{2} \mathcal{E}) + F_1 \tilde{\mathcal{H}} - \frac{x_B}{2-x_B} \left( \frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2 \right) \tilde{\mathcal{E}} \]

- **transversely polarized target:**
  \[ \frac{t}{4M^2} \left[ (2-x_B) F_1 \mathcal{E} - 4 \frac{1-x_B}{2-x_B} F_2 \mathcal{H} \right] \]
  - dominant for the neutron

**Harmonic analysis:**

- measure azimuthal asymmetries in DVCS with respect to beam helicity, beam charge, and/or target polarization

**Cross-section measurement**

(collider example): integration over \( \Phi \)

\[ \frac{d\sigma}{dt} (W, t, Q^2) \approx \frac{4\pi \alpha^2}{Q^4} \frac{W^2 \xi^2}{W^2 + Q^2} \left[ |\mathcal{H}|^2 - \frac{t}{4M^2} |\mathcal{E}|^2 \right] (\xi, t, Q^2) \]
Correction for neutral pions

- Correct unresolved samples.
- No correction for the pure sample since assumed to be free from pions.
- Reconstruct 2-photon asymmetry amplitudes $A_{\text{semi}}$ from real data.
- Determine sidis fraction $f_{\text{semi}}$ and $f_{\text{excl}}$ from MC.
- Correct $A_{\text{meas}}$ in each bin:

$$A_{\text{final}} = \frac{A_{\text{meas}} - f_{\text{semi}}A_{\text{semi}} - f_{\text{excl}}A_{\text{excl}}}{1 - f_{\text{semi}} - f_{\text{excl}}}$$

- Propagate statistical uncertainty and correct (increase) $\delta A_{\text{meas}}$ for removal of events.
- Systematic uncertainty:

$$\delta A_{\text{syst.}}^{\text{bg}} = \frac{1}{2} |A_{\text{final}} - A_{\text{meas}}|$$
Example for “all-in-one” systematic uncertainty: VGG variant 1

Effects from smearing, finite bin width and acceptance
(for some data samples, also alignment)

Sys = generated minus reconstructed amplitude

-0.5
-0.2

0

0.2

A_{LU}sin(2\phi)

A_{LU}sin(\phi)

overall -t [GeV^2] x_B Q^2 [GeV^2]
**VGG model**

- Based on double distributions. Factorized or Regge ansatz. With or w/o D-term. Variable skewness parameters $b_{\text{val}}$ and $b_{\text{sea}}$.

- Used to display model curves: stand-alone VGG code. At HERMES available in two versions: the original one from Vanderhaeghen “VGG01” and a later one from Guidal “VGG05”. Width of model band comes from variation of $b_{\text{val}}$ and $b_{\text{sea}}$.

- Used for systematics: “leading-order type” only (no twist 3 [?])
  - Reconstruction with HERMES gmcDVCS MC. Models 1–5.
  - Generation with “qplot” code, which contains “fast VGG” models 1–5

---


Momentum reconstruction with the recoil detector
Proton / Pion Separation

Combine up to 9 layers to determine log-likelihood PID value:

\[ \text{PID} \equiv \log \frac{\mathcal{P}(\Delta E|\text{proton}, p)}{\mathcal{P}(\Delta E|\text{pion}, p)} \]

p<450 MeV/c, PIDcut=0: pion contamination \(\approx 0.1\%\)
proton efficiency >99%
Commissioning of Recoil Analysis

- Reconstruct e and γ in the traditional way
- Calculate expected kinematics $K_{\text{exp}}$ of recoil proton from e & γ kinematics
- Measure kinematics $K_{\text{meas}}$ of recoil proton
- Missing kinematics: $\Delta K = K_{\text{meas}} - K_{\text{exp}}$

Hermes 2007 data

HERMES 2007 data

• Rho event candidates
  - Exists positive Recoil Track
  - $\Delta p < 0.8$ cut

• DVCS event candidates
  - Exists positive Recoil Track
  - $\Delta p < 1$ cut

HERMES 2007 data

- $\Delta E_{\pi\pi}$ [GeV]
- $M_{x}^{2}$ [(GeV/c)^2]
- $\Delta p$ [GeV/c]
- $\Delta \phi$ [rad]
HERMES polarized target

Internal target of pure gas

Atomic Beam Source: generation of target polarization

Storage Cell

Longitudinally polarized deuteron

System for monitoring polarization

Beam
EML method for amplitude extraction

\[- \log L_{\text{EML}} = - \sum_{i=1}^{N} \log(1 + P_i A_{LU,i}(\phi)) + N\]

\[A_{LU} = A_{LU}^{\cos(0\phi)} + A_{LU}^{\sin \phi} \sin \phi + A_{LU}^{\sin(2\phi)} \sin(2\phi)\]

\[N = \frac{L}{L_{P\to}} \sum_{i,P\to} \frac{(1 + \langle P \rangle A_{LU,i}(\phi))}{1 - \langle \frac{P\to}{P\to} \rangle} + \frac{L}{L_{P\leftarrow}} \sum_{i,P\leftarrow} \frac{(1 + \langle P \rangle A_{LU,i}(\phi))}{1 - \langle \frac{P\leftarrow}{P\leftarrow} \rangle}\]

\[\rightarrow\leftarrow: \text{beam helicity } +1/ -1, \quad \langle P \rangle: \text{effective beam polarization}\]

\[A_{LU}^{\cos(0\phi)}: \text{test of normalization, should be compatible with zero for beam-helicity asymmetry}\]
Beam-Charge Asymmetry on $p$ and $d$
Beam-Helicity Asymmetry on $p$ and $d$
Coherent vs. incoherent

eA→eAγ  eA→e(A-1)Nγ

Coherent contribution rapidly decreasing with -t

BH (proton) ≫ BH (neutron) due to elastic electric form factor

Deuteron: probe spin-1 object
Nucleon: probe spin-1/2 object

Data
Monte Carlo sum
incoherent BH + DVCS
coherent BH + DVCS
BH with resonance exc.

1000 \cdot \frac{N_γ}{N_{βp}}

\( -t \) [GeV^2]
### Asymmetries on polarized deuterons

<table>
<thead>
<tr>
<th>Lepton charge</th>
<th>Target population (deuterons)</th>
<th>Beam helicity</th>
<th>Coherent sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>$\Lambda = +1$</td>
<td>$\Rightarrow$</td>
<td>$\lambda = +1$</td>
</tr>
<tr>
<td>-1</td>
<td>$\Lambda = -1$</td>
<td>$\Leftarrow$</td>
<td>$\lambda = -1$</td>
</tr>
<tr>
<td>0</td>
<td>$\Lambda = 0$</td>
<td>$\Rightarrow$</td>
<td></td>
</tr>
</tbody>
</table>

- **HERMES data set available**
- **Not all combinations of beam-charge and beam-helicity available!**
The Future of DVCS

- Jefferson Laboratory
  - Hall A (E07-007 for p, E08-025 for n): Interference-DVCS$^2$ separation and $Q^2$-dependence of total cross-section (2010)
  - CLAS: transversely polarized HD-Ice target (2012)
  - JLab 12 GeV upgrade: $Q^2_{\text{max}} = 13...14$ GeV$^2$, $e^+$ beam
- @ CERN
  - 2008-09: DVCS test runs, small Recoil detector
  - 2012-15: GPD H, large Recoil detector: beam-charge and -spin asys + x-section
  - 2015+ (?): GPD E, transversely polarized target

- Future Electron-Ion Collider
  - ELIC @ JLab or eRHIC @ BNL: $\sqrt{s} = 20-70$ GeV (HERMES: 7 GeV)
  - ENC @ GSI: $\sqrt{s} = 40$ GeV, ...
  - LHeC
DVCS measurements over the years

H1 @ DESY cross-section 2001
ZEUS @ DESY cross-section 2003
HERMES BCA 2006
CLAS LTSA 2006
HERMES TTSA 2008
HERMES pol-H, -D; nuclear 2010
COMPASS @ CERN: program with Recoil > 2013

CLAS @ JLab BSA
HERMES @ DESY BSA
Zeus @ DESY BSA

H1 BCA 2009
CLAS BSA 2007
H1 BCA 2011
HERMES results with recoil and entire data set 1996-2007

Hall A @ JLab cross-section (p,n) 2010

List does not claim to be exhaustive.

criedl@illinois.edu - HERMES DVCS Results