Hard Exclusive Reactions Measured with HERMES

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The HERMES Spectrometer

- Luminosity Chambers
- Drift Chambers
- FC 1/2
- Target Cell
- DVC
- MC 1-3
- Hodoscope H0
- Field Clamps
- Preshower (H2)
- Steel Plate
- Calorimeter
- Drift Chambers
- Trigger Hodoscope H1
- Rich
- 270 mrad
- IRON WALL
- e+ 27.5 GeV
- 140 mrad
- 170 mrad
- 270 mrad
- 170 mrad
- 140 mrad
- Muon Hodoscopes
- Wide Angle
- Front Muon Hodo
- Magnet

- Silicon E, d, i, r, a, d, A, v, e, i, t, y, a, n, t, e, m, e, r, O, n, s, i, t, e, T, u, r, r, a, l, DE, S, Y, 1, 3.
- 0.7
- 0.2
- 10
- polarised e± beam
- polarised H, D targets
The HERMES Spectrometer

- polarised $e^\pm$ beam ($\leftrightarrow$)
- polarised H, D targets ($\leftrightarrow, \perp$)
- open geometry
- excellent particle ID
Generalised Parton Distributions

- Form factor
- $p_z \rightarrow \infty$

- $\rho(b_\perp)$

- $f(x, b_\perp)$
respectively the helicity and unit charge of the beam lepton. The quantities Here, \((DVCS)\) and \((BH)\) processes.

Figure 2

\[
\begin{align*}
q_1 &= \gamma, \\
q_2 &= \gamma^*, \\
K_{01} &= e, \\
K_{02} &= e, \\
N &= N, \\
N &= N
\end{align*}
\]

Identical final states exploit interference

Bethe - Heitler
respectively the helicity and unit charge of the beam lepton. The quantities
here, (DVCS) and (b) Bethe–Heitler (BH) processes.

Figure 2
Deeply Virtual Compton Scattering (DVCS)

Identical final states exploit interference

Generalised Parton Distributions (via Compton Formfactors)

Bethe - Heitler

Form-factors
**Kinematics and Definitions**

\[ \nu = E - E' \]

\[ Q^2 = 4EE' \sin^2 \frac{\theta}{2} \]

\[ x = \frac{Q^2}{2M\nu} \quad y = \frac{\nu}{E} \]

\[ W^2 = M^2 + 2M\nu - Q^2 \]

\[ z = \frac{E_h}{\nu} \]

\[ p_T^h = p^h \sin \theta^h \]
Beam Spin Asymmetry: access to the imaginary part of CFF $H$

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Beam Charge Asymmetry: access to the real part of CFF $\mathcal{H}$

Beam Spin Asymmetry: access to the imaginary part of CFF $\mathcal{H}$
considered. The average beam-axis location was determined by fitting space-point quadruples, with treated, whereby space-points belonging to already accepted four-space-point tracks are no longer taking energy-deposition-correlated combinations of 1D coordinates, while for the SFT all geo-

The 1D coordinates from the two sides of a SSD sensor or from adjacent parallel and stereo sub-

surrounds the detector assembly. Also shown are examples of tracks reconstructed from two, three, and surrounding the detector assembly. Also shown are examples of tracks reconstructed from two, three, and

Figure 3

The momentum of each track is refitted including energy deposition in the SSD under the 

because of multiple scattering.

momenta is achieved by combining the information on the curvature in the magnetic field with 

studies were performed based on Monte Carlo data. In figure 

fractional momentum resolution 

luminosities of the two beam-helicity states. 

The momentum in the event, as calculated from its four-momentum and that of the incident beam 

this analysis because a clean selection of recoil protons is already accomplished by kinematic event 

10 mrad, respectively, for proton momenta larger than 0.5 GeV, deteriorating for lower momenta 

energy depositions in the SSD. The azimuthal- and polar-angle resolution is about 4 mrad and 

momenta is achieved by combining the information on the curvature in the magnetic field with 

momenta is achieved by combining the information on the curvature in the magnetic field with 

Figure 3
Recoil Event Reconstruction

Figure 5

1000×(N/N_{DIS})

unresolved sample  unresolved-reference sample  pure sample

1000×(N/N_{DIS})

M_X^2 [GeV^2]

M_X^2 [GeV^2]

M_X^2 [GeV^2]

0  5  10  15

0  5  10  15

0  5  10  15

0  0.05  0.1  0.15  0.2

0  0.05  0.1  0.15  0.2

0  0.05  0.1  0.15  0.2

10^{-1}  10^{0}  10^{1}  10^{2}

-10^{-1}  10^{0}  10^{1}  10^{2}

1  10

process fractions

overall  -t [GeV^2]  x_B  Q^2 [GeV^2]

ep→epγ  ep→eΔ^+γ

unresolved  unresolved-reference  pure

experimental data  simulation (sum)  ep→epγ  ep→eΔ^+γ  ep→eΔ^+γ  semi-inclusive
Kinematically Pure Results

- only sin Φ contributes (parity conservations)
- constrains GPD H
- pure data show increased amplitude
Comparison with Theory

In figure 8, the asymmetry amplitudes extracted from the pure sample are compared with calculations \[42\], labeled “VGG Regge”, from the GPD model described in ref. \[43\]. Variants of this model differ in the \(t\) dependence of GPD \(H\). Here, a Regge-inspired ansatz for the \(t\) dependence is used. The skewness dependence is controlled by the \(b\) parameter, where \(b_{\text{val}} (b_{\text{sea}})\) is a free parameter for the valence (sea) quarks. The result of the model calculation depends only very weakly on the value of \(b_{\text{val}}\). For the sea quarks, the skewness-independent variant of the model \(b_{\text{sea}} = 1\) is consistent with the data, while a maximal skewness dependence \(b_{\text{sea}} = 1\) is disfavoured.

Also shown in the figure are the results from model calculations \[44\] labeled “KM”. This model is a dual representation of GPDs with very weakly entangled skewness and \(t\) dependences. The \(t\) dependence is approximated by a physically motivated Regge dependence. The model is constrained by previous measurements at HERMES, Jefferson Lab, and the collider experiments at Hera. The fits resulting in the solid curves disregard data from experiments at Hall A at Jefferson Lab (KM10a), while the dashed curves include these data (KM10b). The KM calculations agree well with the extracted leading amplitude.

The observed difference between the asymmetries extracted from the pure and the unresolved-reference samples is qualitatively consistent with that predicted by a model calculation \[45\] using a soft pion theorem based on chiral symmetry and a \(\Lambda(1232)\)-resonance model using the large \(N_c\) limit to relate the GPDs for excitation to those for the nucleon ground state. In this comparison, it is important to note that the kinematic conditions for this model correspond approximately to the third \(t\) bin of the present measurement.

- constrains GPD \(H\)
- trend in kinematic dependence reproduced by VGG
- maximal skewness (--- - - -) disfavoured
ep → eγπ⁰p

Detecting p in recoil detector in addition
\( e^+ p \rightarrow e^+ \gamma \pi^+ n \)

Detecting \( \pi^+ \) in recoil detector in addition
\[eN \rightarrow e'N'\omega\]

Vector Meson Kinematics

**lepton scattering plane**

**lepton production plane**

**ω decay plane**

**ω production plane**

\[\omega \rightarrow \pi^+ \pi^- \pi^0\]
good agreement between experimental and simulated data. The 20% for the entire kinematic region and increases from events to the total number of events. It amounts to about which is calculated as the ratio of number of background Carlo simulation that is normalized to data in the region histograms represent semi-inclusive deep-inelastic scattering for deuteron data, with the PDG \[the reasonable agreement of the fit result, exclusively produced\].

The distributions of missing energy for deuteron data, with the PDG \[the reasonable agreement of the fit result, exclusively produced\].

\[\omega\] Event Selection

PYTHIA SIDIS

exclusive PYTHIA simulation
\[ r_{1-1}^1 + \text{Im}(r_{1-1}^2) = 0 \]
\[ = -0.004 \pm 0.038 \pm 0.015 \]
\[ = -0.033 \pm 0.049 \pm 0.004 \]
\[ \text{Re}(r_{10}^5) + \text{Im}(r_{10}^6) = 0 \]
\[ = -0.024 \pm 0.013 \pm 0.004 \]
\[ = -0.001 \pm 0.016 \pm 0.005 \]
\[ \text{Im}(r_{10}^7) - \text{Re}(r_{10}^8) = 0 \]
\[ = -0.060 \pm 0.100 \pm 0.018 \]
\[ = -0.104 \pm 0.110 \pm 0.023 \]
Natural vs Un-natural Parity Exchange

- Natural Parity Exchange: \( J^P = 0^+, 1^-, \ldots \)
- Un-natural Parity Exchange: \( J^P = 0^-, 1^+, \ldots \)

\[
P = \frac{d\sigma_N^T - d\sigma_U^T}{d\sigma_N^T + d\sigma_U^T} \approx \frac{2r_{1-1}^1 - r_{00}^1}{1 - r_{00}^{04}}
\]
The UPE-to-NPE asymmetry of the transverse cross section does not hold in exclusive production. This model appears to fully account for the unnatural-parity contribution to the data.

The GK model calculations with and without inclusion of the pion-pole contribution demonstrate the clear need to include the pion-pole contribution. For the deuteron data, compared to the case of exclusive production, this ratio is about four times smaller, for the proton and deuteron.

\[
R = \frac{d\sigma_L(\gamma_L \rightarrow V)}{d\sigma_T(\gamma_T \rightarrow V)} \approx \frac{1}{\epsilon 1 - r_{04}^{00}}
\]
Summary and Conclusion

- Hard exclusive reactions provide unique access to the quark and gluon dynamics inside nucleons
- Many reactions pioneered at HERMES using the unique combination of polarised $e^\pm$ and (un)polarised H,D targets
- Event sample purified with addition of HERMES recoil detector
- Pure DVCS events show increased amplitude in $A_{LU}$
- $A_{LU}$ in $\Delta$-DVCS measured, constraining transition GPDs
- Extraction of SDME for $\omega$ in exclusive electro-production allows test of SCHC, parity exchanges and longitudinal to transverse cross section ratios