Exclusive Processes at HERMES

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On behalf of the HERMES Collaboration

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Outline

1. Introduction
2. DVCS
3. Pseudoscalar Mesons
4. Vector Mesons
5. Outlook
6. Summary
Polarized beam with polarization around 50%
Possibility of both electron and positron beams
The **HERMES** Spectrometer

- **Internal Polarized Gas Target**
- **Magnet**
- **Tracking Chambers** $\Delta P/P \sim 2\%$
- **Momentum measurement**
- **Lepton/Hadron Separation** with $\epsilon > 99\%$
- **RICH** to separate pion, kaon, proton
- **Calorimeter** $\Delta E_\gamma/E_\gamma \sim 5\%$

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Exclusive processes

- Initial and Final State *fully known*
- HERA Lepton Beam with fixed internal gas target.
- Scattered Lepton and produced meson in Hermes acceptance
- Select Exclusive reactions by putting *constraints* on the missing mass, or missing energy
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**Exclusive Leptoproduction of Mesons/Photons**

- Collins, hep-ph/9907513 -
- Collins, Frankfurt, Strikman, hep-ph/9709336 -

**Factorization** can be applied for exclusive processes:

- a hard part
- a meson distribution amplitude
- a soft part providing information about the nucleon in terms of Generalized Parton Distributions

Factorization valid for large $Q^2$, low $t$ (and $\gamma^*_L$)
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Generalized Parton Distribution Functions

- 4 GPD’s for every quark flavor $q$:
  \[ H_q, E_q, \tilde{H}_q, \tilde{E}_q \]
- Functions of $x$, $\xi$, and $t$
- Contain the standard Form Factors and Distribution functions
- Combining Transverse position and Longitudinal Momentum
- Access to the Total Spin $J^q$ via Ji’s Sum Rule:
  \[
  J^q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} (H^q + E^q) x dx \\
  = \frac{1}{2} (\Delta u + \Delta d + \Delta s) + L^q
  \]
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\[
\begin{align*}
\int_{-1}^{1} dx H^q(x, \xi, t) &= F_1^q(t) \\
\int_{-1}^{1} dx E^q(x, \xi, t) &= F_2^q(t) \\
\int_{-1}^{1} dx \tilde{H}^q(x, \xi, t) &= G_A^q(t) \\
\int_{-1}^{1} dx \tilde{E}^q(x, \xi, t) &= G_P^q(t)
\end{align*}
\]

\[
H^q(x, 0, 0) = q(x) \\
\tilde{H}^q(x, 0, 0) = \Delta q(x)
\]
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Both different final states and different observables select different combinations of GPD’s:

- Exclusive Pseudoscalar Meson Production: $\bar{H}, \bar{E}$
- Exclusive Vector Meson Production: $H, E$
- Deeply Virtual Compton Scattering: $H, E, \bar{H}, \bar{E}$
- Target or Beam related asymmetries access a product of GPD’s.
- Cross Section Measurements give access to quadratic combination.
Observing Generalized Parton Distributions

Both different final states and different observables select different combinations of GPD’s:

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Deeply Virtual Compton Scattering

⇒ Probe $E$ and $H$ (and $\bar{E}, \bar{H}$)
\[ e + p \rightarrow e + p + \gamma \]

- **DVCS** final state indistinguishable from the **Bethe-Heithler** final state, where a Brehmsstrahlung photon is created.
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Select final state by putting constraints on the Missing Mass.
$e + p \rightarrow e + p + \gamma$

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- Select Final state by putting constraints on the Missing Mass
- Amplitudes add up coherently:

$$d\sigma = \left|\tau_{BH} + \tau_{DVCS}\right|^2 = \left|\tau_{BH}\right|^2 + \left|\tau_{DVCS}\right|^2 + \frac{1}{2} \left(\tau_{BH}\tau^*_{DVCS} + \tau^*_{BH}\tau_{DVCS}\right)$$

$$\propto c_0 + \sum_n c_n \cos(n\phi) + \lambda \sum_n s_n \sin(n\phi)$$
**DVCS** final state indistinguishable from the Bethe-Heithler final state, where a Brehmsstrahlung photon is created.

Select Final state by putting *constraints* on the Missing Mass

Amplitudes add up coherently:

\[
\begin{align*}
\frac{d\sigma}{d\Omega} &= |\tau_{BH} + \tau_{DVCS}|^2 \\
&= |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \left(\tau_{BH}^* \tau_{DVCS}^* + \tau_{BH}^* \tau_{DVCS}\right)
\end{align*}
\]

\[
\propto c_0 + \sum_n c_n \cos(n\phi) + \lambda \sum_n s_n \sin(n\phi)
\]

**Beam Related Asymmetries:**

**BSA:**

\[
d\sigma(\vec{e}^+p) - d\sigma(\vec{e}^-p) \sim \sin(\phi) \times \text{Im} M_{\text{unp}}^{1,1}
\]

**BCA:**

\[
d\sigma(e^+p) - d\sigma(e^-p) \sim \cos(\phi) \times \text{Re} M_{\text{unp}}^{1,1}
\]
Beam Spin Asymmetry

\[ A_{LU} = \frac{1}{<|P_B|>} \frac{N^+ (\phi) - N^- (\phi)}{N^+ (\phi) + N^- (\phi)} \propto \sum n s_n \sin (n\phi) \]

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

HERMES PREL. 2000 (refined)

P1 = -0.04 ± 0.02 (stat)
P2 = -0.18 ± 0.03 (stat)
P3 = 0.00 ± 0.03 (stat)

\(<-t> = 0.18 \text{ GeV}^2, <x_B> = 0.12, <Q^2> = 2.5 \text{ GeV}^2\)

• expected \sin(\phi) behavior!
Beam Charge Asymmetry

$$A_C = \frac{N^+(\phi)-N^-(\phi)}{N^+(\phi)+N^-(\phi)} \propto c_0 + \sum_n c_n \cos(n\phi) + \lambda \sum_n s_n \sin(n\phi)$$

- expected $\cos(\phi)$ behaviour
- $\sin(\phi)$ moment due to polarized beam
Beam Charge Asymmetry

\[ A_{C}^{\cos \phi}(t) \] can distinguish between models
- GPD model with factorized t-dependence (dotted) with D-term (dash-dotted)
- GPD model with Regge-inspired t-dependence (solid) with D-term (dashed)
From Asymmetries to GPD’s

\[ M_{\text{unp}}^{1,1} = F_1(t) \mathcal{H}_1(\xi, t) + \frac{x_B}{2-x_B} (F_1(t) + F_2(t)) \tilde{\mathcal{H}}_1(\xi, t) - \frac{t}{4M^2} F_2(t) \mathcal{E}_1(\xi, t) \]

- \( F_1(t) \) and \( F_2(t) \) Dirac and Pauli Form Factors
- \( \mathcal{H}_1, \tilde{\mathcal{H}}_1 \) and \( \mathcal{E}_1 \) Compton Form Factors
From Asymmetries to GPD’s

\[ M_{\text{unp}}^{1,1} = F_1(t) H_1(\xi, t) + \frac{x_B}{2-x_B} (F_1(t) + F_2(t)) \tilde{H}_1(\xi, t) - \frac{t}{4M_p^2} F_2(t) \mathcal{E}_1(\xi, t) \]

- \( F_1(t) \) and \( F_2(t) \) Dirac and Pauli Form Factors
- \( H_1, \tilde{H}_1 \) and \( \mathcal{E}_1 \) Compton Form Factors

\begin{align*}
< x_B > \sim 0.1 \text{ and } < -t > \sim 0.1 \text{GeV}^2 \\
\text{BSA : } & \propto \text{Im} H_1 \propto \sum_q e_q^2 \left( H^q(\xi, \xi, t) - H^q(-\xi, \xi, t) \right) \\
\text{BCA : } & \propto \text{Re} H_1 \propto \sum_q e_q^2 \left( \int_{-1}^{1} H^q(x, \xi, t) \left( \frac{1}{x-\xi} + \frac{1}{x+\xi} \right) dx \right)
\end{align*}

\( \Rightarrow \) Access to GPD \( H \)!
Transverse Target Asymmetry

During 2002-2005 Hermes run with a transversely polarised target: $<|P_T|> \sim 75\%$

$$A_{UT}(\phi, \phi_S) = \frac{1}{|P_T|} \cdot \frac{N^\uparrow(\phi, \phi_S) - N^\downarrow(\phi, \phi_S)}{N^\uparrow(\phi, \phi_S) + N^\downarrow(\phi, \phi_S)}$$

$$\propto \text{Im}(F_2 \mathcal{H} - F_1 \mathcal{E}) \sin(\phi - \phi_S) \cos(\phi) + \text{Im}(F_2 \tilde{\mathcal{H}} - F_1 \xi \tilde{\mathcal{E}}) \cos(\phi - \phi_S) \sin(\phi)$$
Transverse Target Asymmetry

\[ A_{UT} = \sin(\phi - \phi_s)\cos(\phi) \]

HERMES PRELIMINARY
(in HERMES acceptance)

\[ e^+ p \rightarrow e^+ \gamma X \]
\[ (M_x < 1.7 \text{ GeV}) \]
Transverse Target Asymmetry

\[ A_{UT}^{\sin(\phi - \phi_S) \cos(\phi)} \propto \text{Im}(F_2H - F_1E) \Rightarrow \text{Access to GPD } E ! \]
Pseudoscalar Mesons

⇒ Probe $\tilde{E}$ and $\tilde{H}$
Cross Section:

$$\sigma_{\gamma^* p \rightarrow n + \pi^+}(x, Q^2) = \frac{N^{\pi^+}_{\text{excl}}}{L \cdot \Delta x \Delta Q^2 \cdot \kappa(x, Q^2) \cdot \Gamma(<x>, <Q^2>)}$$

- **L**: Integrated luminosity 1996-2000: 283 pb$^{-1}$
- **$\kappa(x, Q^2)$**: Detection probability (estimated from MC)
- **$\Gamma(<x>, <Q^2>)$**: Virtual photon flux factor

$$\sigma^{\pi^+} \sim (\tilde{H} + \tilde{E})^2$$
Extracting a Cross Section

- Acceptance correction is model dependent, therefore a comparison with 2 different GPD models was made
  - Mankiewicz, Piller & Radyushkin (1999)
  - Vanderhaeghen, Guichon & Guidal (1999)
Extracting a Cross Section

- Acceptance correction is model dependent, therefore a comparison with 2 different GPD models was made.
- Detection probability has to be taken into account.
\[ \sigma_{\text{tot}} : Q^2 \text{ dependence in } x \text{ bins: } \sim (\tilde{H} + \tilde{E})^2 \]

- \( Q^2 \) behavior with respect to \( \sigma_L - \sigma_T \)

Q^2 dependence is consistent with LO expectations, however Vanderhaeghen, Guidal, Guichon model too small

Power corrections (\( k_T \), soft overlap) overestimate data
Testing factorisation theorem predictions $\sigma_{\text{red}}$

- Factorization theorem predicts a $\frac{1}{Q^6}$ dependence for $\sigma_L$ at fixed $x$ and $t$
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- Cross Section can be written as

$$\sigma = \frac{1}{16\pi} \frac{x^2}{1 - x} \frac{1}{Q^4} \frac{1}{1 + \frac{4m^2x^2}{Q^2}} \sum_{\text{spin}} |A(\gamma^* p \rightarrow pM)|^2$$

\begin{align*}
\text{Kinematical} & \quad \text{Factor}
\end{align*}
Testing factorisation theorem predictions $\sigma_{\text{red}}$

- Factorization theorem predicts a $\frac{1}{Q^6}$ dependence for $\sigma_L$ at fixed $x$ and $t$

- Cross Section can be written as

$$
\sigma = \frac{1}{16\pi} \frac{\chi^2}{1 - x} \frac{1}{Q^4} \frac{1}{\sqrt{1 + \frac{4m^2x^2}{Q^2}}} \sum_{\text{spin}} |A(\gamma^* p \to pM)|^2
$$

Kinematical Factor

$\sigma_{\text{reduced}}$
Testing factorisation theorem predictions $\sigma_{\text{red}}$

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$$\sigma_{\text{reduced}}$$

pure $\gamma^*_L + \text{LO} \Rightarrow d\sigma_{\text{red}} \sim \frac{1}{Q^2}$
Testing factorisation theorem predictions $\sigma_{\text{red}}$

Fit To data of a $\frac{1}{Q^p}$ function:

\[ p = 1.9 \pm 0.5 \quad p = 1.7 \pm 0.6 \quad p = 1.5 \pm 1.0 \]
Vector Mesons

⇒ *Probe E and H*
**Introduction**

**DVCS**

**Pseudoscalar Mesons**

**Vector Mesons**

**Outlook**

**Summary**

\[ e^+ p \rightarrow e^- p + \rho^0 \]

- \( \rho^0 \) reconstructed from \( h^+ h^- \) pairs
- Exclusivity constraints by requiring \( \text{Missing Energy} \Delta E \) to be 0, describe background shape by MC
- Evidence of exclusive \( \rho^0 \) production
\( e^+ p \rightarrow e^+ p + \rho^0 \)

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- Evidence of exclusive $\rho^0$ production

\[
\begin{array}{c|cc}
\chi^2/\text{ndf} & 153.5 & 58 \\
\text{Constant} & 480.8 \pm 16.77 \\
\text{Mean} & 0.3600 \pm 0.1533\times10^{-1} \\
\text{Sigma} & 0.4144 \pm 0.1353\times10^{-1} \\
\end{array}
\]
Target Spin Asymmetry $A_{UT}$ for $e^+ p \rightarrow e + p + \rho^0$

$$A = \frac{1}{|S_\perp|} \left( \int_0^\pi \sigma(\beta) d\beta - \int_\pi^{2\pi} \sigma(\beta) d\beta \right) \left/ \int_0^{2\pi} \sigma(\beta) d\beta \right.$$  

- Sensitivity to $J^u$
- At Hermes asymmetry slope predicted to be positive
Target Spin Asymmetry $A_{UT}$ for $e^+ p \rightarrow e + p + \rho^0$


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- Sensitivity to $J^u$
- At Hermes asymmetry slope predicted to be positive

\[
\sin(\phi - \phi_S) \text{ amplitude of asymmetry: } A_{UT}^{\sin(\phi - \phi_S)} \sim -A \propto E \cdot H
\]
Target Spin Asymmetry $A_{UT}$ for $e^+ p \rightarrow e^+ p + \rho^0$

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Increasing statistics by including all transverse data will allow for an $\sigma_L - \sigma_T$ separation
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Data consistent with theory predictions
Stay Tuned!

- Transverse Target Asymmetry for exclusive $\pi^+$
  - Theoretical prediction – Frankfurt et Al., Phys. Rev. D60 (1999), 2 models with different pion form factor
  - Data under analysis!

![Graph showing transverse spin asymmetry versus $x_{bj}$ for different values of $-t$ and $Q^2$]
Stay Tuned!

- Transverse Target Asymmetry for exclusive $\pi^+$
- Exclusive $\pi^0$ production analysis ongoing
  - no pion-pole contribution
  - information about $\tilde{H}$ only

Mankiewicz et. al.
Stay Tuned!

- Transverse Target Asymmetry for exclusive $\pi^+$
- Exclusive $\pi^0$ production analysis ongoing
- A Recoil Detector surrounding the target cell is currently being commissioned, and will allow a direct measurement of exclusive reactions.
Summary

1. Factorization theorem for hard exclusive processes allows GPD’s to be probed
2. DVCS probes the GPD’s $H$ and $E$ via asymmetries
   - BCA and BSA give access to $H$
   - $A_{UT}$ allows $E$ to be parametrized, giving access to $J''$
3. Cross Section for exclusive $\pi^+$ production
   - Comparison with GPD based model
   - $Q^2$ dependence in agreement with theory
4. $A_{UT}$ for exclusive $\rho^0$ production gives additional constraints on $H$ and $E$
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Cross Section for exclusive $\pi^+$ production
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$A_{UT}$ for exclusive $\rho^0$ production gives additional constraints on $H$ and $E$

Last Word:
Thanks for Listening!
$$e + p \rightarrow e + X + \pi^+$$

\[ M_X^2 = (P_e + P_p - (P_{e'} + P_h))^2 \]

doesn’t allow separation of exclusive events from the non-exclusive background
**e + p → e + X + π⁺**

\[ M_X^2 = (P_e + P_p - (P_{e'} + P_h))^2 \]

This doesn't allow separation of exclusive events from the non-exclusive background.

- **Solution:** Use the normalised \( \pi^- \) yield as an estimate for the background (\( e + p \rightarrow e + n + \pi^- \)).
\[ e + p \rightarrow e + n + \pi^+ \]

\[ M_X^2 = (P_e + P_p - (P_{e'} + P_h))^2 \]
doesn’t allow separation of exclusive events from the non-exclusive background

Solution: Use the normalised \( \pi^- \) yield as an estimate for the background \((e + p \rightarrow e + n + \pi^-)\).

Exclusive Peak at nucleon mass, mean and width like exclusive Monte Carlo, based on a GPD model
A Recoil Detector for HERMES

- Silicon measuring low momenta protons
- SciFi for momentum and tracking
- Photon detector to improve exclusivity
- Superconducting Magnet providing field for SciFi
- A new collimator to reduce background hits