Latest results on hard exclusive processes at HERMES

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Outline

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HERMES experiment

Generalized parton distributions

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- Exclusive meson production

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Study of spin structure of the nucleon at HERMES

- Longitudinal spin/momentum structure, hadronization
- Transverse spin/momentum structure $\rightarrow$ transversity, TMDs
- DVCS, exclusive meson production $\rightarrow$ GPDs, “nucleon tomography”
- Strange-baryon production
Study of spin structure of the nucleon at HERMES

- Longitudinal spin/momentum structure, hadronization
- Transverse spin/momentum structure → transversity, TMDs
- DVCS, exclusive meson production → GPDs, “nucleon tomography”
- Strange-baryon production
Longitudinally polarized electron (positron) beams
P=27.57 GeV/c
Gas targets:
• Longitudinally polarized H, D
• Unpolarized H, D, 4He, N, Ne, Kr, Xe
• Transversely polarized H

Beam:
• Longitudinally polarized e⁺ and e⁻ with both helicities
• Energy 27.6 GeV

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Latest results on hard exclusive processes at HERMES
Generalized Parton Distributions (GPDs)

- Include Form Factors (FFs) and Parton Distribution Functions (PDFs) as moments and forward limits
- Multidimensional description of nucleon structure
- Access to the quark total angular momentum via Ji relation

$$\mathcal{J}_q = \lim_{t \to 0} \int dx \int \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right]$$
Access to GPDs via exclusive processes

- Sensitivity of different final states to different GPDs
- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$
- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ flip nucleon helicity
- DVCS ($\gamma$) $\rightarrow$ $H, E, \tilde{H}, \tilde{E}$
- Vector mesons ($\rho, \omega, \phi$) $\rightarrow$ $H, E$
- Pseudoscalar mesons ($\pi, \eta$) $\rightarrow$ $\tilde{H}, \tilde{E}$
Deeply Virtual Compton Scattering (DVCS)
(more details in talk of Dietmar Zeiler: HK 16.4)

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
Azimuthal asymmetries in DVCS

**Cross section**

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

**Beam-charge asymmetry**

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

**Charge-difference beam-helicity asymmetry**

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

**Charge-averaged beam-helicity asymmetry**

\[
A^{DVCS}_{LU}(\phi) = \frac{\left(\sigma^{++} - \sigma^{+-}\right) - \left(\sigma^{+-} - \sigma^{--}\right)}{\left(\sigma^{++} + \sigma^{+-}\right) + \left(\sigma^{+-} + \sigma^{--}\right)} = \frac{1}{D(\phi)} \frac{x_B^2 t P_1(\phi) P_2(\phi)}{Q^2} s_1^{DVCS} \sin(\phi)
\]

Measurements of these beam-helicity asymmetries allow to separate contributions from DVCS and interference term

This separation is impossible in measurements of single-charge beam-helicity asymmetry

\[
A_{LU}(\phi) = \frac{\sigma^{--} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}
\]
DVCS event selection, uncertainties and corrections

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

Kinematic requirements

\[0.03 < x_B < 0.35\]
\[1 \text{ GeV}^2 < Q^2 < 10 \text{ GeV}^2\]
\[-t < 0.7 \text{ GeV}^2\]
\[E_\gamma > 5 \text{ GeV}\]
DVCS asymmetries and connections with GPDs

HERMES DVCS

- Beam charge asymmetry $GPD \ H$
- Beam helicity asymmetry $GPD \ H$
- Transverse target spin asymmetry $GPD \ E$
- Longitudinal target spin asymmetry $GPD \ \tilde{H}$
- Double spin asymmetry $GPD \ \tilde{\tilde{H}}$

Red - *JHEP 11 (2009) 083*
Results on beam-charge and beam-helicity asymmetry amplitudes in DVCS

JHEP 11 (2009) 083

$A_{C \cos \phi} \propto \Re[F_1 H]$  

$A_{L,U,I \sin \phi} \propto \Im[F_1 H]$  

Higher twist

Comparisons with GPD model, Vanderhaeghen, Guichon, Guidal


Resonance fraction from $ep \rightarrow e\Delta^+ \gamma$ is about 12%
Transverse target polarization asymmetry in DVCS

JHEP 06 (2008) 066

Sensitivity of GPD model predictions to $J_u$ at fixed $J_d = 0$
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, Strikman [PRC 68 (2003) 015204]

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

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

\[ A_{LU, nucleus}^{\text{sin} \phi} / A_{LU, proton}^{\text{sin} \phi} \propto \frac{A}{Z} \]
Guzey, Siddikov [JPG 32 (2006) 251]
Analysis of DVCS on nuclear targets

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

- 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: \( \langle -t \rangle = 0.018 \text{ GeV}^2 \)
  - incoherent: \( \langle -t \rangle = 0.20 \text{ GeV}^2 \)

- Results on beam-charge asymmetries for \(^4\text{He, N, Ne}\) and beam-helicity asymmetries for

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

\[
^4\text{He, N, Ne:} \quad A_{LU}^I(\phi) = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}
\]

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Latest results on hard exclusive processes at HERMES
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.
Exclusive vector meson production

\[ \rho \]

\[ \phi \]

\[ \omega \]
Exclusive vector meson production

Modified perturbative approach
S. V. Goloskokov and P. Kroll, EPJ C 50, 829 (2007)

\[ A \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2 / \mu^2)) \otimes \Phi(z, k_\perp; \mu^2) \]

- Factorization for \( \sigma_L \) (and \( \rho_L, \omega_L, \varphi_L \)) only

- \( \sigma_L - \sigma_T \) suppressed by \( 1/Q \)

- \( \sigma_T \) suppressed by \( 1/Q^2 \)

- Power corrections: \( k_\perp \) is not neglected

- Regulate the singularity in the transverse amplitude

- \( \gamma^*_\perp \rightarrow \rho^0_\perp \) transitions can be calculated (model dependent)
  - \( \rho^0 \): contributions from \( \tilde{H} \) and \( \tilde{E} \)
  - \( \pi^* \): contributions from \( H_T \) and \( \tilde{H}_T \)
Exclusive vector meson production

\[
\frac{d\sigma}{dx_B dQ^2 dt d\phi_s d\phi d\cos \theta d\phi} \approx \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \phi_s, \phi, \cos \theta, \phi)
\]

Production and decay angular distributions decomposed:

\[
W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}
\]

beams \( P_l \)

W \( XY \)

target \( S_L, S_T \)
Exclusive vector meson production

\[
\frac{d\sigma}{dx_B dQ^2 dt d\phi d\phi d \cos \theta d \phi} \approx \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \phi_s, \phi, \cos \theta, \phi)
\]

- Parameterized by helicity amplitudes

M. Diehl, JHEP09 (2007) 064

- Or by Spin Density Matrix Elements (SDMEs)
Exclusive $\rho^0$ event selection

$\Delta E = (M_X^2 - M_p^2)/2M_p$

- Background subtraction with PYTHIA
  - $\langle Q^2 \rangle = 2.3 \text{ GeV}^2$, $\langle W \rangle = 4.9 \text{ GeV}$
  - $\langle x_B \rangle = 0.07$, $\langle -t \rangle = 0.13 \text{ GeV}^2$
\( \rho^0 \) unpolarized SDMEs

**EPJ C62 (2009) 659**

- Unpolarized SDMEs: \( W_{UU} \)
- Beam-polarized SDMEs: \( W_{UL} \)
- Hierarchy confirmed experimentally
- Proton and deuteron data consistent
- \( s \)-channel helicity conservation:
  - \( \rho^0 \) conserves the helicity of \( \gamma^* \)
  - significant \( \gamma^*_L \to \rho^0_L \) and \( \gamma^*_T \to \rho^0_T \)
  - a substantial interference
- \( s \)-channel helicity violation
  - significant \( \gamma^*_T \to \rho^0_L \)
  - smaller \( \gamma^*_L \to \rho^0_T \) and \( \gamma^*_{-T} \to \rho^0_T \)
  - \( 2 - 10 \sigma \) level violation

**Hierarchy of \( \rho^0 \) amplitudes:**

\[ |T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{1-1}|^2 \]
\( \rho^0 \) transverse SDMEs

**PLB 679 (2009) 100**

- **Transverse SDMEs:** \( W_{UT} \)
- **Measured for the first time**
- **Average kinematics:**
  - \( \langle -t' \rangle = 0.13 \text{ GeV}^2 \)
  - \( \langle x_B \rangle = 0.09 \)
  - \( \langle Q^2 \rangle = 2.0 \text{ GeV}^2 \)
- **Related to proton helicity-flip amplitude**
- **Suppressed by** \( \sqrt{t} / 2M_p \)

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Latest results on hard exclusive processes at HERMES
\( \rho^0 \) transverse target spin asymmetry

### Connection with GPDs

\[
A_{UT}^{\sin(\phi - \phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g}
\]

### Compatible with zero overall value

\[
A_{UT}^{\sin(\phi - \phi_s)} = -0.033 \pm 0.058
\]
Connection of $\rho^0$ transverse target spin asymmetry to GPDs

- Asymmetry in terms of GPDs
  \[ A_{UT}^{\sin(\phi - \phi_s)} \propto \frac{E}{H} \propto \frac{E^q + E^g}{H^q + H^g} \]

- Parameterization for $H_q, H_{\bar{q}}, H_g$
  - $E_g$ is related to the total angular momenta $J_u$ and $J_d$.
  - Predictions for $J_d = 0$
  - $E_{\bar{q}}, E_g$ are neglected

- Data favours positive $J_u$
  - Statistics too low to reliably determine the value of $J_u$ and its uncertainty
  - Within the statistical uncertainty in agreement with theoretical calculations
  - Indication of small $E_{\bar{q}}, E_g$?

- Other GPD model calculations
ω transverse target spin asymmetry

- Low statistics - no $ω_L/ω_T$ separation
- Predictions for large $\sin(\phi - \phi_s)$ asymmetry amplitude
  \[ A_{UT}^{\sin(\phi - \phi_s)} \approx -0.1 \]
- Indication of negative $\sin(\phi - \phi_s)$ asymmetry amplitude
  \[ A_{UT}^{\sin(\phi - \phi_s)} = -0.22 \pm 0.16_{\text{stat}} \pm 0.11_{\text{syst}} \]
- No contradiction with $ρ^0$ predictions
  \[ A_{UT}^{ρ^0,\sin(\phi - \phi_s)} \propto \Im\left( \frac{2E^u + E^d}{2H^u + H^d + H^g} \right) \]
  \[ A_{UT}^{ω,\sin(\phi - \phi_s)} \propto \Im\left( \frac{2E^u - E^d}{2H^u - H^d} \right) \]
\( \pi^+ \) transverse target spin asymmetry

- **Leading asymmetry amplitudes:** small

- **Subleading asymmetry amplitude:** surprisingly large, expected to be suppressed by \( 1/Q (\gamma^*_L - \gamma^*_T \text{ interference?}) \)

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Ch. Bechler, D. Müller, *arXiv:0906.2571*


Exclusivity at HERMES: Recoil detector

- 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 measurement without and with Recoil Detector

Pre-Recoil data
- Scattered lepton and photon were detected in the forward spectrometer
- Recoil proton was not detected
- Exclusivity achieved via missing mass technique
- Associated processes were not resolved (12% contribution in the signal)

Recoil data
- Detection of recoil proton
- Suppression of background to <1% level
DVCS event selection with the Recoil detector

- **Missing mass for Monte Carlo**
  - No requirement for Recoil
  - Positively charged Recoil track
  - Kinematic fit probability > 1%
  - Kinematic fit probability < 1%

- **Fit works well for Monte-Carlo**
  - After chi-square cut associated Bethe-Heitler and semi-inclusive background is suppressed to negligible level

- **For data optimization of measurement errors of kinematic parameters is necessary**
  - Preliminary optimization done
  - Systematic studies are in progress
First signal of exclusive $\pi^0$ production at HERMES

- Can provide access to chiral-even and chiral-odd GPDs
- Impossible without recoil proton detection
- With recoil information clear signal is observed

Recoil proton required

Cuts on momentum and angle difference applied
Conclusion

HERMES produced and published many results on exclusive processes
- DVCS
- Exclusive vector meson production
- Exclusive pseudoscalar meson production

New results will be presented and published soon