Abstract
Hard exclusive production in deep inelastic lepton scattering provides new access to the poorly known Generalized Parton Distributions of the nucleon. Different observables for hard exclusive production of photons and mesons have been measured by the HERMES experiment. Emphasis is given to recent results which help to determine the total angular momentum of quarks in the proton.

1 Introduction
The analysis of hard exclusive processes can be used to investigate the generalized parton distributions (GPDs) [1]. From a formal point of view, GPDs show a continuity in describing both inclusive and exclusive processes, the usual parton distributions being a kinematic limit of GPDs. Also, the elastic form factors are specific moments of GPDs. Strong interest in the formalism of GPDs has emerged after GPDs were found to offer the first possibility to reveal the total angular momentum carried by the quarks and gluons in the nucleon.

In this paper, the latest results obtained by the HERMES experiment on Deeply Virtual Compton Scattering (DVCS) and exclusive meson production are reviewed [2]. The data presented here were collected using internal, longitudinally or transversely polarized or unpolarized hydrogen and deuterium targets with longitudinally polarized 27.6 GeV positrons (electrons) in the HERA storage ring at DESY.

2 Deeply Virtual Compton Scattering
The basic mechanism for DVCS (in electroproduction) is a quark absorbing a virtual photon and radiating a real photon. At large photon virtuality, the process amplitude is a convolution of a hard scattering term exactly calculable in perturbative QCD, and a soft (non perturbative) term [3]. The soft term describes the nucleon transition in the process, and is parameterized by the four leading-twist GPDs which conserve quark helicity, $H$, $E$, $\tilde{H}$, and $\tilde{E}$. In hard exclusive processes like DVCS, a direct extraction of the GPDs from experimentally measured observables can in general not be performed because at the amplitude level, GPDs are convolved with the hard scattering term, and cannot be disentangled. As a consequence, models of GPDs have to be used to calculate observables that can be compared to corresponding experimental results. The convolved $H$, $E$, $\tilde{H}$, and $\tilde{E}$ terms are traditionally represented with the symbols $\mathcal{H}$, $\mathcal{E}$, $\tilde{\mathcal{H}}$, and $\tilde{\mathcal{E}}$, respectively.

Experimentally, for electroproduction of photons, one cannot disentangle the DVCS from the Bethe-Heitler (BH) process, where the virtual photon is absorbed by the nucleon target and a real photon is emitted by either the incoming or the outgoing lepton. Within the HERMES kinematical acceptance, the DVCS cross section is at least one order of magnitude smaller than...
the BH cross section [4]. Nevertheless, the DVCS amplitude can still be accessed through the BH-DVCS interference term, which can be projected out by considering specific cross section asymmetries in the azimuthal angle $\phi$. The latter is defined as the angle between the incoming and outgoing lepton trajectories and the plane correspondingly defined by the virtual and the real photon.

The event selection at HERMES requires events with exactly one photon and one charged track, identified as the scattered lepton, with $Q^2 > 1$ GeV$^2$, where $-Q^2$ is the squared four-momentum of the initial virtual photon. The recoiling proton is not detected, and exclusive events are identified by requiring the missing mass $M_X$ of the reaction $ep \rightarrow e' \gamma X$ to correspond to the proton mass. Due to the finite energy resolution, the exclusive sample is selected in the region $1.5 < M_X < 1.7$ GeV, based on signal-to-background studies using Monte Carlo simulations.

For an unpolarized target, the beam-charge cross section asymmetry $A_C(\phi)$ with unpolarized lepton of either charge, and the beam-spin cross section asymmetry $A_{LU}(\phi)$ using a longitudinally polarized positron beam, at leading-twist in the HERMES kinematics reduce to [4]

$$A_C(\phi) \equiv \frac{d\sigma(e^+ p, \phi) - d\sigma(e^- p, \phi)}{d\sigma(e^+ p, \phi) + d\sigma(e^- p, \phi)} \propto \cos \phi \cdot Re(F_1 \mathcal{H}),$$

$$A_{LU}(\phi) \equiv \frac{d\sigma(e^+ p, \phi) - d\sigma(e^- p, \phi)}{d\sigma(e^+ p, \phi) + d\sigma(e^- p, \phi)} \propto \sin \phi \cdot Im(F_1 \mathcal{H}),$$

where $F_1$ is the Dirac form factor of the proton. The first measurement of the asymmetry $A_C$ was performed by HERMES using a hydrogen target. The dependence of the $\cos \phi$ moment on the squared four-momentum transfer $t$ to the target is shown in the left panel of Fig. 1, and compared with predictions in the GPD framework based on [5] (VGG) with different assumptions on the
The longitudinal target-spin cross section asymmetry $A_{UL}(\phi)$ for an unpolarized positron beam, at leading-twist is expected to reduce [7], in the HERMES kinematics, to

$$A_{UL}(\phi) \left( \frac{d\sigma(e^+ p, \phi) - d\sigma(e^+ p, \phi)}{d\sigma(e^+ p, \phi) + d\sigma(e^+ p, \phi)} \right) = \sin \phi \cdot \Im \left( F_1 \hat{H} + \frac{x_B}{2-x_B} (F_1 + F_2) \hat{H} \right),$$

where $F_2$ is the Pauli form factor of the proton. The $\phi$-dependence of the longitudinal target-spin asymmetry on a hydrogen target is shown in Fig. 2, where the fit results show the expected non-zero leading-twist sin $\phi$ modulation of the asymmetry. The $\sin 2\phi$ moment is $3\sigma$ different from zero, an indication that higher-twist effects might contribute to $A_{UL}$ in the HERMES kinematics.

A useful observable to access the convolved GPDs $\xi$ and $\tilde{\xi}$ is the transverse target-spin asymmetry with unpolarized beam $A_{UT}(\phi - \phi_S)$, which in the HERMES kinematics reads

$$A_{UT}(\phi - \phi_S) \left( \frac{d\sigma(\phi - \phi_S) - d\sigma(\phi - \phi_S + \pi)}{d\sigma(\phi - \phi_S) + d\sigma(\phi - \phi_S + \pi)} \right) \propto \Im \left( F_2 \hat{H} - F_1 \hat{E} \right) \cdot \sin(\phi - \phi_S) \cos \phi + \Im \left( F_2 \hat{H} - F_1 \frac{x_B}{2-x_B} \hat{E} \right) \cdot \cos(\phi - \phi_S) \sin \phi,$$

where $\phi_S$ denotes the azimuthal angle between the target polarization plane with respect to the lepton plane. The kinematical dependences of the moments $A_{UT}^{\sin(\phi - \phi_S) \cos \phi}$ and $A_{UT}^{\cos(\phi - \phi_S) \sin \phi}$ on transversely polarized hydrogen target are shown in Fig. 3. Also shown are the predictions [8] based on the VGG code [5] with different ansatze for the parameterizations of GPDs [9].
displayed curves represent the moments evaluated for a set of $u$-quark total angular momentum values $J_u$, as a model parameter for $E$, and for a fixed value of the $d$-quark total angular momentum $J_d = 0$, as inspired by the results of recent lattice calculations [10].

By comparing the measured moment and the moment predicted for different $J_u$ and $J_d$ assumptions (relaxing the condition $J_d = 0$) using the VGG code, the quantity $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ is calculated from

$$\chi^2(J_u, J_d) = \sum_{\text{kin bins}} \frac{\left| A_{UT,i}^{\sin(\phi - \phi_2) - \cos(\phi)} \right|^2}{\delta A^2_{\text{stat},i} + \delta A^2_{\text{syst},i} + \delta A^2_{\text{accept},i}}.$$  

The area in the $(J_u, J_d)$-plane, in which the $\Delta \chi^2$ value is not larger than unity is defined as the one-standard-deviation constraint on $J_u$ versus $J_d$, and is shown in Fig. 4. This HERMES result, described by the relation $J_u + J_d/2.9 = 0.42 \pm 0.21 \pm 0.06$, provides the first GPD model-dependent constraint on the total angular momenta $J_u$ and $J_d$.

3 Exclusive Meson Production

Another process to access GPDs is the exclusive production of mesons by hard longitudinal virtual photons. In the Bjorken limit the process amplitude can be factorized similarly to the DVCS case, with one additional soft part describing the hadronization of virtual partons into the final meson state [11]. Validity of factorization has been demonstrated only for longitudinal photons. Nevertheless, compared to the longitudinal cross section, the cross section for transversely polarized photons was shown to be suppressed by a factor $1/Q^2$.

While the leading order amplitude factorization holds, interesting selection rules among produced mesons and probed GPDs in the target nucleon arise, due to quantum numbers conservation in the QED and QCD processes involved [11]. As an example, longitudinally polarized...
**Fig. 4:** Model-dependent constraint on the total angular momentum $J_u$ vs $J_d$, obtained by comparing the data and theoretical predictions on the moment $A_{UT}^{\sin(\phi - \phi_S)} \cos \phi$. As described in the text, the $t$-dependence of the GPDs is modeled using the Regge ansatz. The impact of this choice, compared to its alternatives, was found to be negligible. The $D$-term contribution to the GPDs is set to zero, as suggested by the results on the beam-spin asymmetry.

Vector meson channels are sensitive only to the unpolarized GPDs ($H$ and $E$). Additionally, flavor singlet and non-singlet combinations of unpolarized GPDs can be separately accessed by measuring either vector mesons or meson states with quantum numbers of the $f$-meson family [12]. In contrast, DVCS depends at the same time on both unpolarized and polarized GPDs.

### 3.1 Hard Exclusive $\rho^0_L$ Meson Production

Exclusive longitudinal $\rho^0$ events, generated from scattering positrons or electrons off transversely polarized proton target, were identified by detecting the scattered leptons and the produced $h^+h^-$ hadron pairs. The invariant mass of the two-hadron system $m_{2\pi}$ was determined assuming both hadrons to be pions. The requirement $0.6 < m_{2\pi} < 1.0$ GeV was used to select exclusive resonant pion pairs produced in the decay $\rho^0 \rightarrow \pi^+\pi^-$. In addition, the missing energy $\Delta E$ of the events was required to be lower than 0.6 GeV, assuming the undetected recoiling target to be a proton. The non-resonant exclusive pion background was estimated to be a few percent, and the data were not corrected for it. Due to the limited experimental missing mass resolution, the analyzed exclusive reaction $e\pi \rightarrow e\rho^0 \rightarrow e\pi^+\pi^-$ cannot be separated unambiguously from semi-inclusive background which can be smeared into the exclusive region. This contribution was estimated using a PYTHIA simulation, and the data were corrected for it.

From the exclusive events, the transverse target spin asymmetry for longitudinal $\rho^0$ production was determined by using the unbinned maximum likelihood method. The $x$- and $t$-dependence of the extracted asymmetry moment $A_{UT}^{\sin(\phi - \phi_S)}$ are shown in Fig. 5.

### 3.2 Hard Exclusive $\pi^+\pi^-$ Production

Hard exclusive pion pair production may involve both resonant and non-resonant channels mainly through the quark exchange mechanism which is dominant at HERMES kinematics. The pion pairs can be generated with the values of the strong isospin $I$, total angular momentum $J$, and...
C-parity of either a $\rho$-meson ($I = 1, J = 1, 3, \ldots, C = -1$), or an $f$-meson ($I = 0, J = 0, 2, \ldots, C = +1$). The quark exchange with $C = +1$ and $C = -1$ is described by flavor singlet and non-singlet $H$ and $E$ combinations [12], respectively. The latter cannot be accessed by analyzing $\rho^0$ decay. The interference between the two isospin channels provide information on the weaker isoscalar channel at the amplitude level.

For the purpose of studying the interference between $\pi^+\pi^-$ production in $P$-wave ($I = 1$) and $S, D$-wave states ($I = 0$), the Legendre moment $\langle P_1(\cos \theta) \rangle$ [13] is particularly useful because it is only sensitive to such interference. Here $\theta$ is the polar angle of the $\pi^+$ meson with respect to the direction of the $\pi^+\pi^-$ pair in the pions rest-frame, and $P_1$ is the first-order Legendre polynomial.

The first experimental data for hard exclusive $\pi^+\pi^-$ pair production on hydrogen and deuterium targets have been reported by HERMES. The Bjorken $x$-dependence of $\langle P_1 \rangle$ is shown...
in Fig. 6 in the $\pi^+\pi^-$ invariant mass $m_{\pi\pi}$ region around the $\rho^0$ meson resonance. For both targets $\langle P_1 \rangle$ is non-zero, which we interpret as originating from the interference of the resonant $\rho^0$ $P$-wave with non-resonant $S$-wave $\pi^+\pi^-$ production. The moment increases in magnitude with $x$, suggesting that the exchange of flavor non-singlet quark GPD combinations ($C' = -1$) becomes competitive with the dominant singlet exchange ($C = +1$).

4 Conclusions
Several observables in DVCS, hard exclusive $\rho^0_L$ and $\pi^+\pi^-$ production have been measured, and compared with GPD-based predictions in order to provide constraints on GPDs. The first GPD model-dependent constraint on the total angular momenta $J_u$ and $J_d$ has been obtained.

References