EXCLUSIVE PHYSICS AT HERMES AND COMPASS*

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HERMES and COMPASS results of DVCS and DVMP are presented. Preparations for the 2016/17 COMPASS GPD run are at full swing.

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1. Hard exclusive reactions

For about one and a half decades, data from hard exclusive reactions have provided access to nuclear structure. In this seldom case, the nucleon or nucleus does not fragment when probed by the lepton, but emits a real photon (Deeply Virtual Compton Scattering, DVCS) or meson (Deeply Virtual Meson Production, DVMP). The extra particle carries away information about nucleon structure. The soft, non-perturbative part of hard exclusive reactions can be described in the framework of Generalized Parton Distributions (GPDs), which provide a tomographic picture of the nucleon: slices of transverse parton density distributions in longitudinal-momentum space ("transverse imaging"). For greater details, see [1].

Sufficient kinematic information must be available for the tagging of exclusive events, *i.e.* no particles emerging from the reaction other than the beam lepton, the target nucleon, and the produced real photon or meson. If detector resolutions are sufficient, it may not be necessary to detect all particles for the selection of an exclusive data sample by utilizing missing-mass techniques. The analysis of the experimental data aims at extracting Fourier amplitudes of asymmetries with respect to spin and/or charge of beam and target. These asymmetries parametrize the harmonic modulation of the cross section in azimuthal angles between momentum planes of the

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involved particles, or the target spin direction. For DVCS, the scattering amplitude interferes with the amplitude of the Bether–Heitler process (BH), which has the same initial and final states as DVCS.

2. DVCS results from HERMES

HERMES used the longitudinally polarized HERA (DESY) 27.6 GeV electron beam to scatter off a target of unpolarized or polarized gas. For DVCS data collected between 1996 and 2005, only the beam electron and the photon were detected. The DVCS/BH samples are corrected for π^0 background. The 1996–2005 single-photon data are diluted by in average 12% with events for that the proton is excited to a resonant state. In 2006/07, a recoil detector [2] was, therefore, installed to detect the intact target proton and to allow for selection of a truly exclusive DVCS/BH sample without nucleon resonances. With detection of protons with momenta as low as 125 MeV, the minimum reachable $-t$ is 0.016 GeV^2 in DVCS. The HERMES average kinematic values are $\langle x_{\rm B}\rangle = 0.1$, $\langle Q^2\rangle = 2.5$ GeV^2, and $\langle -t\rangle = 0.12$ GeV^2 ($\langle -t\rangle = 0.13$ GeV^2) without (with) proton detection.

The HERMES DVCS/BH set on proton and deuteron targets comprises beam-spin, beam-charge, longitudinal target-spin, and transverse target-spin asymmetries. The availability of two HERA beam charges, and the possibility to set beam spin and charge independently of each other allows for the separation of the DVCS and interference amplitudes. Figure 1 gives an overview. For the event sample with recoil-proton detection, the amplitudes of the beam-spin asymmetry were extracted using kinematic fitting of the measured electron, photon, and proton kinematics [3], see Fig. 2. Comparison to amplitudes extracted from a data sample under comparable kinematic conditions, but without recoil-proton detection, indicates that the amplitudes from the "pure" DVCS/BH sample are slightly larger in magnitude, an increase that is compatible with the removal of a diluting asymmetry from resonant production of zero magnitude. This is confirmed by the extraction of beam-spin asymmetries in $ep \to e\gamma(\pi N)$ in the Δ-resonance region from HERMES data [4]: they are compatible with zero.

The unique set of HERMES deep-inelastic scattering data on heavier nuclear targets allows to search also for effects beyond those of proton structure. The data on unpolarized and longitudinally polarized deuterons (including a dedicated tensor-polarized data set) were investigated for coherent and tensor signatures, which are expected to be enhanced for low values of squared momentum transfer $-t$, when the virtual photon does not probe the individual (spin-1/2) nucleons but the nucleus as a whole. The DVCS/BH amplitudes at low $-t$ are sensitive to GPDs arising for a spin-1 deuteron in addition to those for a spin-1/2 proton. The DVCS/BH beam-spin and -charge asymmetries of unpolarized helium, nitrogen, neon, krypton, and

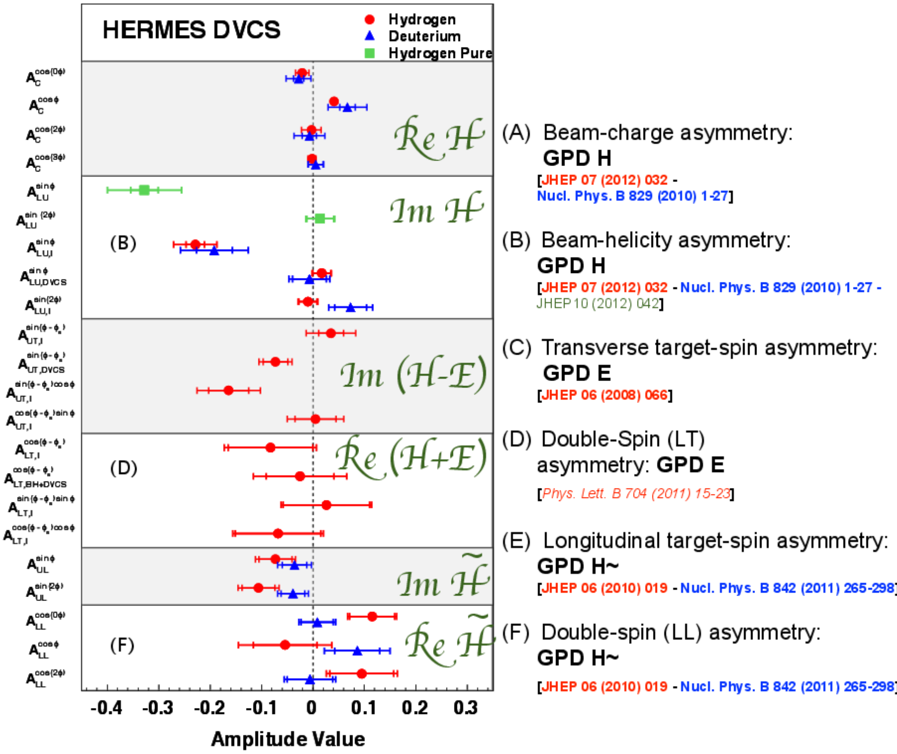

Fig. 1. (Color on-line) HERMES DVCS/BH asymmetry amplitudes on proton (red dots) and deuteron (blue triangles) targets.

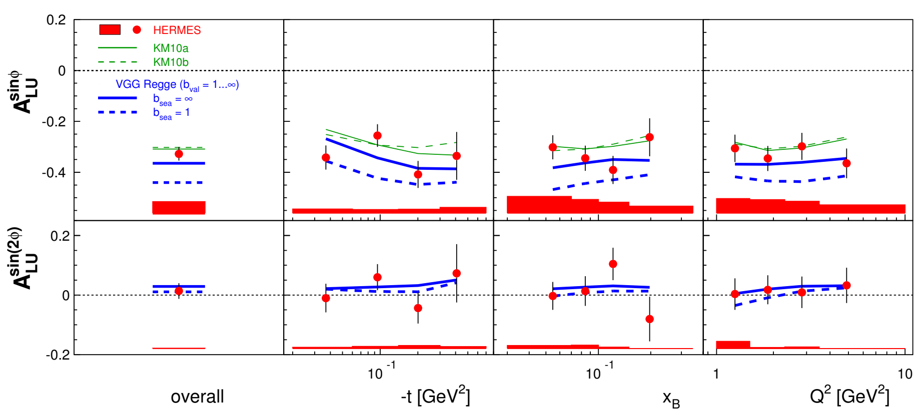

Fig. 2. HERMES DVCS/BH beam-spin asymmetry amplitudes with recoil-proton detection.

xenon were investigated for an A-dependence to search for nuclear effects [5]. The experimental uncertainties of these pioneering measurements are too large to claim discovery of any of such signatures.

3. DVCS at COMPASS

COMPASS uses the longitudinally polarized SPS (CERN) 160 GeV muon beam to scatter off an unpolarized or polarized target. Between 2002 and 2010, the recoil proton has not been detected. For the selection of an exclusive DVCS/BH sample, recoil-proton detection is required at COMPASS. A successful GPD pilot run with recoil detector CAMERA was carried out in 2012 with $0.06\ \mathrm{GeV}^2 < -t < 0.8\ \mathrm{GeV}^2$. From these data, exclusive single-photon events were selected in three different bins of x_{B} (Fig. 3): a BH reference yield at small x_{B}; a medium-x_{B} sample dominated by the DVCS/BH interference term for the extraction of harmonic modulations in the DVCS cross section; and a sample of pure DVCS at high-x_{B} for the study of transverse imaging from the ϕ-integrated cross section. For greatest purity of the latter, the BH and π^0 yields were subtracted. The BH yield was estimated by normalizing the simulated data to the measured data in the lowest x_{B}-bin. The visible π^0 yield is excluded from these data and the invisible π^0 background (one decay photon below the DVCS threshold) is subtracted using the maximum contribution obtained from different Monte Carlo generators. No radiative corrections are applied and no decay photons from radiatively produced pions are considered.

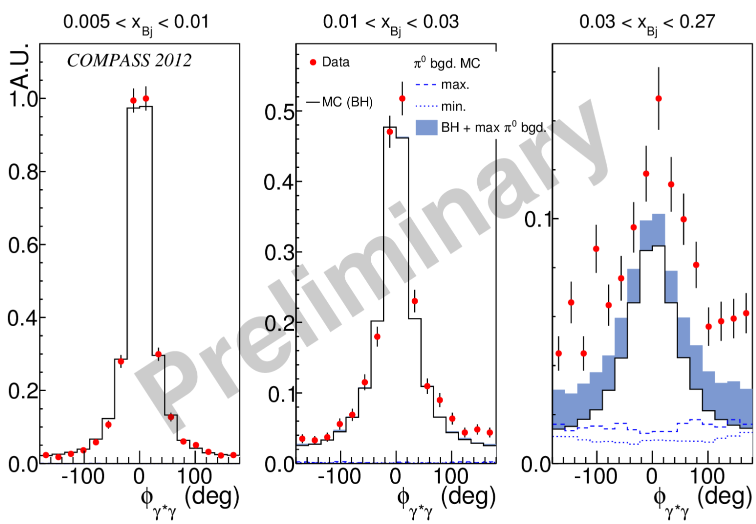

Fig. 3. Exclusive single-photon events from COMPASS 2012 data in different x_{B} bins as function of the azimuthal angle ϕ between lepton scattering plane and the plane defined by the virtual and real photons. See the text for details.

A one-bin extraction of the b-slope from the differential cross section $d\sigma/dt \propto \exp(-b|t|)$ is possible already from 2012 data and in progress. The projected experimental uncertainties of the sum and difference of cross sections with opposite muon polarization and charge, and the beam-spin/-charge asymmetry from the 2016/17 GPD run are given in [1].

4. Results from DVMP

Detection of the scattered beam lepton and meson decay products allows for the selection of exclusive-meson samples at HERMES and COMPASS. The non-exclusive background is simulated and subtracted. For the COMPASS exclusive ρ sample (proton target), $\langle x_{\mathrm{B}}\rangle = 0.04$, $\langle Q^2\rangle = 2.2$ GeV^2, and $\langle p_{\mathrm{T}}\rangle = 0.18$ GeV^2.

4.1. Spin Density Matrix Elements

The cross section of DVMP can be parametrized in terms of Spin Density Matrix Elements (SDMEs), which describe the helicity transfer from the virtual photon to the vector meson. Longitudinal and transverse helicity states can be separated by measuring the meson decay angles with respect to the meson momentum, utilizing the self-analyzing characteristic of the process. From HERMES data in exclusive ρ^0, ϕ, and ω production, SDMEs have been extracted [6]. While the first two sets obey the expected hierarchy in magnitudes, the ω SDMEs violate this hierarchy and indicate a significant role of Unnatural Parity Exchange (an exchange of quantum numbers between virtual photon and vector meson that does not correspond to the quantum numbers of the vacuum). Ratios of ω SDMEs were analyzed using a set of GPDs extracted from HERMES exclusive ρ^0, ϕ, and π^+ data [7]. The phenomenological approach predicts the ω data well only when the contribution from the pion pole is included.

4.2. Transverse asymmetries

The $\sin(\phi-\phi_S)$ amplitude of the transverse target-spin asymmetry A_{UT} in hard exclusive leptoproduction of real photons or vector mesons can constrain GPD E, which is linked to quark orbital angular momentum. ρ^0 and ω mesons differ in their linear combination of quark states and thus allow to filter GPDs of different quark flavors. E^{ρ^0} is expected to be suppressed with respect to E^{ω}. Indeed, measurements of $A_{\mathrm{UT}}^{\sin(\phi-\phi_S)}$ of the ρ^0 are compatible with zero for both HERMES [8] and COMPASS [9] (Fig. 4), while preliminary results for the ω from both experiments indicate non-vanishing values. Yet the experimental uncertainties do not allow to unambiguously constrain the sign of the $\pi\omega$ transition form factor [7]. The $\sin\phi_S$ amplitude of A_{UT}

is sensitive to the chiral-odd GPD H_{T}, which is related to the transversity Transverse Momentum Dependent PDF. The COMPASS measurement for ρ^0 mesons (Fig. 4) yields a non-vanishing value of $A_{\mathrm{UT}}^{\sin\phi_S}$, providing evidence for the existence of GPD H_{T}.

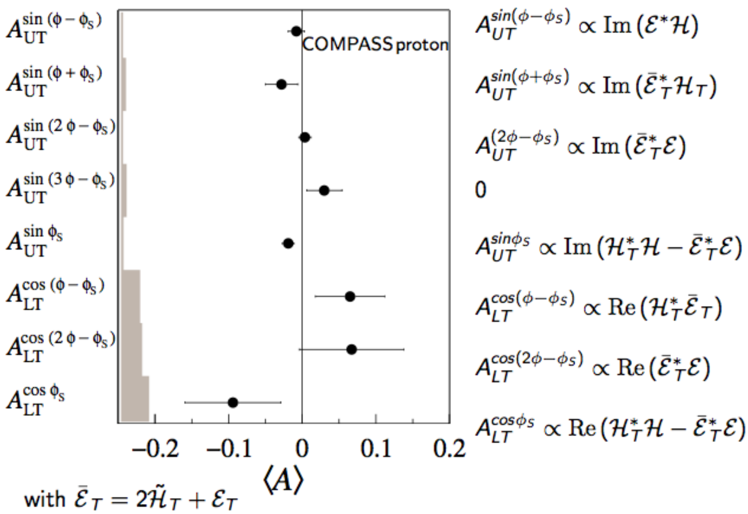

Fig. 4. Amplitudes of the transverse target-spin asymmetry in hard exclusive leptoproduction of ρ^0 mesons from COMPASS data. Results from Ref. [9] and comments written on the right courtesy by Ref. [10].

5. Global analysis of experimental data and outlook

The global analysis of hard exclusive data (*e.g.* [11,12]) aims at providing predictions for future measurements; at tests of GPD universality by comparing predictions based on DVMP data with observables extracted from DVCS data; at constraints of GPDs at $\xi = x$; or constraints of the real and imaginary parts of Compton Form Factors related to GPDs. The rich set of HERMES DVCS amplitudes will remain unique in the near future. During the 2016/17 GPD run using a liquid hydrogen target and recoil detector, CAMERA, COMPASS will collect data in the so far unexplored kinematic domain between HERMES and the Jefferson Laboratory experiments on the one side, and the HERA collider experiments on the other side. The future COMPASS results in DVCS are awaited by the community. Of particular interest is the magnitude of $\cos\phi$ amplitude of the spin/charge-asymmetry at COMPASS since it has been measured to change sign between H1 (HERA) and HERMES kinematics. The COMPASS DVCS data will provide further inputs to the constraint of GPD H, while data from DVCS and DVMP will allow for transverse imaging of the nucleon. The GPD run is scheduled to start in April 2016. A potential second GPD run after 2017 with a transversely polarized NH_3 target and a new recoil detector would provide more information on GPD E from DVCS data, and on GPD E and chiral-odd GPDs from DVMP data.

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