Single-spin azimuthal asymmetries at HERMES

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Abstract.
Recent HERMES results for single-spin asymmetries in the azimuthal distribution of pions and photons are presented. SSA in semi-inclusive pion production provided a first useful information on new types of parton distribution and fragmentation functions. SSA in exclusive pion and photon production allowed a first glimpse of the new Skewed Parton Distributions which were recently introduced for a general description of the structure of the nucleon.

1. Introduction

The main goal of the HERMES experiment at DESY is the complete study of the structure of the nucleon.

The complete twist-2 description of the nucleon requires three sets of structure functions: the unpolarised structure functions, the longitudinal spin distribution functions and the still unmeasured transverse spin distribution functions. A classification of the complete set of distribution functions at the twist-2 and twist-3 levels can be found in [1].

The unpolarised structure functions have been studied by several experiments over the last three decades and are presently one of the main subjects of a deeper investigation of the ZEUS and H1 experiments at DESY.

The polarised structure functions have also been studied by several experiments over the last decade and presently HERMES results represent the most complete and precise data set for proton, neutron and deuteron polarised structure function g_1 [2].

Both unpolarised and polarised structure functions are studied by inclusive Deep Inelastic Scattering of high energy leptons.

In contrast, transversity distributions are still unmeasured because of their particular chiral-odd nature which implies that they are not directly observable in inclusive lepton scattering experiments [3]. In absence of relativistic effects, the transversity distribution h_1 is equal to the helicity distribution g_1. Therefore a measurement of h_1 reveals the relativistic nature of the quarks in the nucleon. Also the Q^2 evolution of h_1 is different from g_1 due to the absence of mixing of quarks with

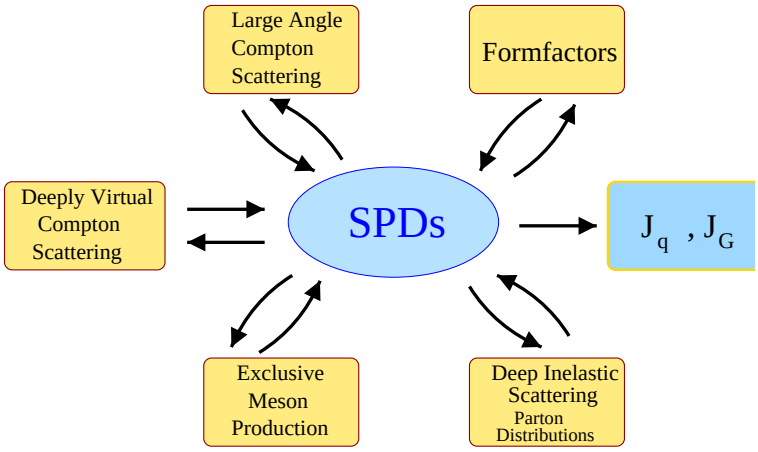

Figure 1. Connection of SPDs (GPDs) with different observables

gluons. Finally the first moment of h_1 provides a way to measure the tensor charge of the nucleon which can be calculated with lattice QCD.

Very recently a new and powerful description of the structure of the nucleon has been introduced within the formalism of the Skewed Parton Distributions (SPDs or GDPs) [4]. These new functions offer the possibility to construct a complete map of the nucleon's wavefunction and to provide a common framework for different observables like form factors, parton distributions, Compton scattering, exclusive meson production (see fig. 1). In particular, SPDs offer the unique possibility to provide information on the orbital angular momentum of the quarks. To access these functions a new type of experiment is required: hard exclusive scattering.

In my presentation, I will describe how the very powerful tool of the single-spin azimuthal asymmetry distribution has been used in the HERMES experiment to access transversity distributions for Semi-Inclusive DIS (SIDIS) reactions and GPDs for exclusive reactions.

2. Single-spin azimuthal asymmetry in SIDIS

Transversity distributions are predicted to be measurable in semi-inclusive measurements where only the lepton beam *or* the target are polarised [5]. In the case of semi-inclusive pion production from a longitudinally polarised target, the combination of chiral odd quark spin distribution functions and a fragmentation function of the same structure (the Collins chiral-odd time-odd fragmentation function) leads to an asymmetry in the distribution of the azimuthal angle ϕ of the pion around the virtual photon momentum with respect to the lepton scattering plane (see fig. 2). In the naive parton model, where non interacting collinear partons are assumed, the conservation of parity, angular momentum and helicity requires that single-spin azimuthal asymmetries need to vanish. Therefore single-spin azimuthal asymmetries arise from multi-parton correlation and from the role of the intrinsic quark transverse momentum k_T.

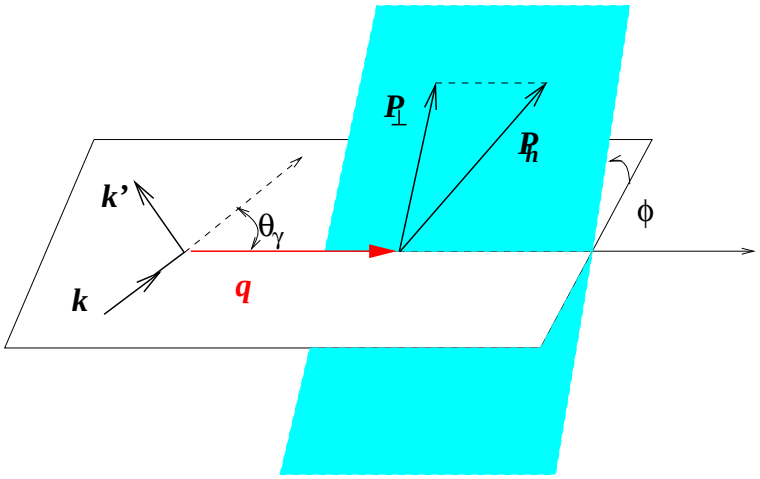

Figure 2. Kinematic planes for pion production

The first measurements of single-spin asymmetries for semi-inclusive charged [6] and neutral [7] pion production in DIS have recently been performed by HERMES by using a 27.5 GeV positron beam on a longitudinally polarised hydrogen target [8]. The average target polarisation was 0.86 with a fractional uncertainty of 5%. The scattered positron, the produced charged pions and the decay photons from π^0 were detected by the HERMES spectrometer [9]. The kinematic requirements imposed on the scattered positrons were $Q^2 \geq 1$ GeV^2, $0.023 \leq x \leq 0.4$, $0.2 \leq y \leq 0.85$ and an invariant mass $W^2 \geq 4$ GeV^2. The pion fractional energy was restricted to the range $0.2 \leq z \leq 0.7$ in order to reduce effects from target fragmentation at low z and from exclusive processes at large z.

In fig. 3 the cross section asymmetries for π^0, π^+ and π^- in SIDIS are shown as a function of the azimuthal angle ϕ:

$$A(\phi) = \frac{1}{|P|}\frac{N_+ - N_-}{N_+ + N_-},$$

where $\pm$ refers to the target spin state of polarisation $|P|$.

The agreement between π^0 and π^+ and the difference to π^- can be interpreted in terms of favoured and unfavoured Collins fragmentation function and in terms of u-quark dominance in the distribution functions.

The $\sin\phi$ moments of the distribution have been extracted according to

$$\mathcal{A}_{UL}^{\sin\phi} = \frac{\frac{L^+}{L_P^+}\int_0^{2\pi}\sin\phi\ \mathrm{d}N_+ \ - \ \frac{L^-}{L_P^-}\int_0^{2\pi}\sin\phi\ \mathrm{d}N_-}{\frac{1}{2}[\int_0^{2\pi}\mathrm{d}N_+ \ + \ \int_0^{2\pi}\mathrm{d}N_-]}$$

where $\pm$ refer to the target spin state, $L^\pm$ are the dead-time corrected luminosities, and $L_P^\pm$ luminosities weighted by the target polarization.

The asymmetries averaged over x and $P_\perp$ are:

$$\pi^+ \quad \mathcal{A}_{UL}^{sin\phi} = \quad 0.022 \pm 0.005(stat) \pm 0.003(syst)$$

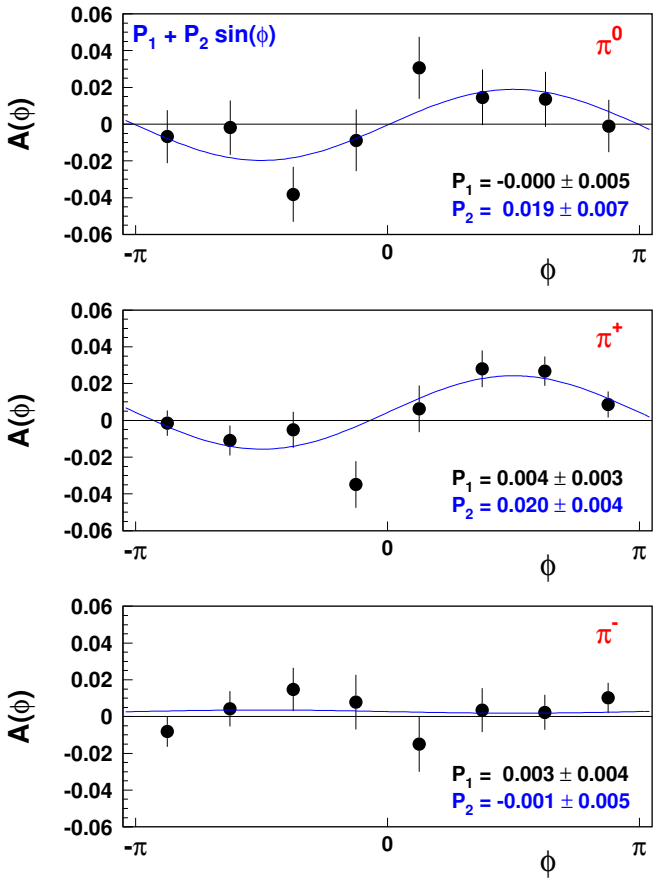

Figure 3. Cross section asymmetries as function of the pion azimuthal angle. Curves are $\sin\phi$ fits to the data.

$$\pi^0 \quad \mathcal{A}_{UL}^{sin\phi} = \ 0.019 \pm 0.007(stat) \pm 0.003(syst)$$
$$\pi^- \quad \mathcal{A}_{UL}^{sin\phi} = -0.005 \pm 0.008(stat) \pm 0.004(syst).$$

The measured asymmetries for π^0, π^+ and π^- are shown in fig. 4 as function of the pion fractional energy z, the inclusive Bjorken variable x and the transverse momentum of pions $P_\perp$. The π^- asymmetries are always consistent with zero. The behaviour of π^0 and π^+ is similar for all the variables. In particular a smooth and monotonic increase with z was found in the SIDIS range. The apparent increase of the effect with x suggests that the effect is associated with valence quark contributions. The increase of $\mathcal{A}_{UL}^{\sin\phi}$ as $P_\perp$ increases up to ~ 0.8 GeV can be related to the dominant role of intrinsic quark transverse momentum when $P_\perp$ remains below a typical hadronic mass scale of 1 GeV.

In fig. 4 is also shown the range of predictions of a model [10] for the π^0 asymmetry in which the twist-3 distribution function h_L has been assumed to be equal to the twist-2 transversity distribution function h_1 : $h_L(x) = h_1(x) - \frac{d}{dx}h_{1L}^{\perp(1)}(x) \sim h_1(x)$. The band represents the variation between the two assumption $h_1 = g_1$ (non-relativistic limit and $h_1 = (g_1 + f_1)/2$ (Soffer inequality). The Collins ansatz for the spin-dependent

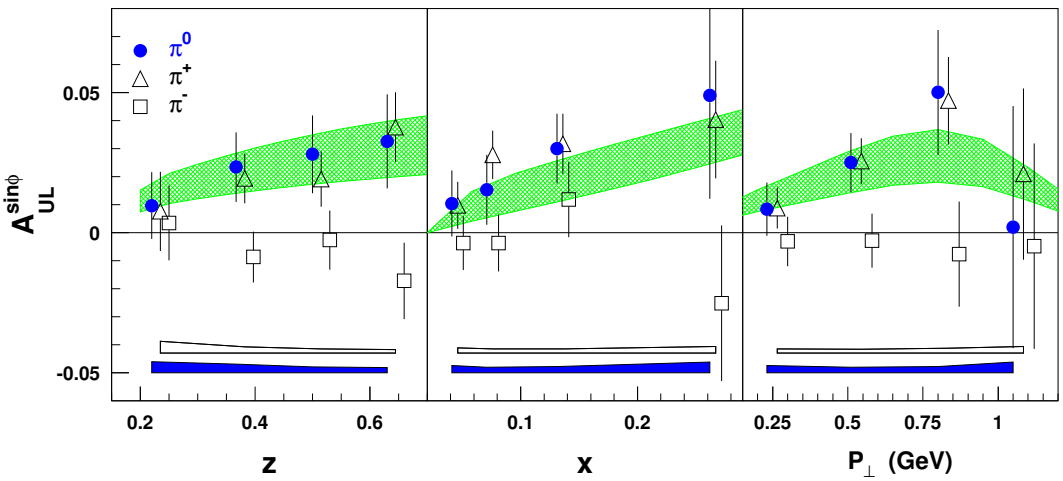

Figure 4. Analyzing power in the $\sin\phi$ moment for pions as a function of the pion fractional energy z, the Bjorken variable x and the pion transverse momentum $P_\perp$. Error bars include the statistical uncertainty only. The filled and open bands at the bottom represent the systematic uncertainties for neutral and charged pions, respectively. The shaded areas show a range of predictions of a model calculation applied to the case of π^0.

time-reversal-odd fragmentation function $H_1^\perp$ was adopted: $A_C(z,k_T) = \frac{|k_T|}{M_h}\frac{H_1^\perp(z,k_T^2)}{D_1(z,k_T^2)} = \frac{M_C|k_T|}{M_C^2+k_T^2}$.

These asymmetries provide the first evidence in support of the existence of non-zero chiral-odd structures that describe the transverse polarisation of quarks. New data are expected from future HERMES measurements on transversely polarised target, which will give direct access to the transversity.

3. Single-spin azimuthal asymmetry in exclusive pion production

In the SPDs framework the nucleon is described by four leading-twist distribution functions which are selected by changing the quantum numbers of the final state in exclusive production:

- Vector mesons: $\rho^0, \omega, \Phi \rightarrow$ unpolarized SPD
- Pseudoscalar mesons: $\pi^0 \rightarrow$ polarized SPD
- Pseudoscalar mesons: $\pi^+ \rightarrow$ polarized SPD + meson exchange
- DVCS: $\gamma \rightarrow$ polarized and unpolarized SPD

In addition, different observables access different combinations of SPDs.

The exclusive π^+ channel which occurs at $z \sim 1$ ($ep \rightarrow e'\pi^+ n$) was identified by using the $ep \rightarrow e'\pi^- X$ SIDIS distribution as a reliable estimate of the background for the $ep \rightarrow e'\pi^+ X$ channel once it is correctly normalized outside the exclusive region. In fig. 5 the background subtraction procedure and the remaining exclusive π^+ peak

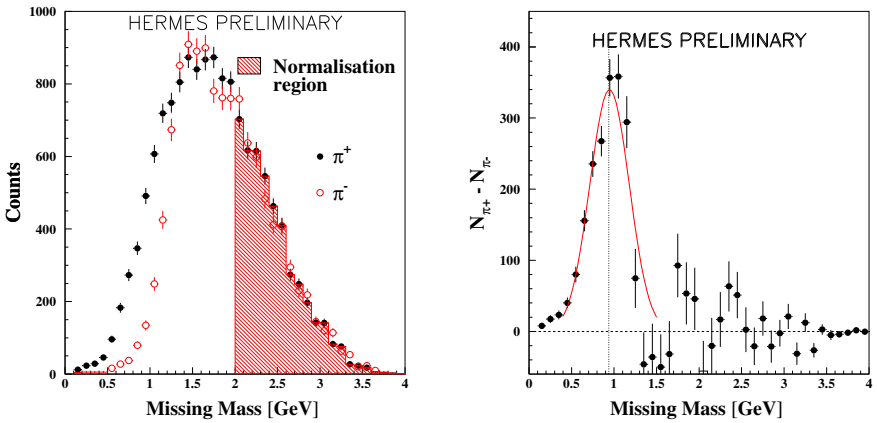

Figure 5. Measured π^+ and π^- yields as a function of missing mass (left). The right figure shows the difference of π^+ and normalized π^- yield versus missing mass, resulting in a clear peak around the nucleon mass indicated by the line.

is shown. Within the current experimental setup a missing-mass resolution of 0.2 GeV was obtained from the data for values of M_X around the nucleon mass in agreement with a Monte Carlo simulation based on a SPD event generator [11].

The exclusive sample was defined for events with $M_X \leq 1.05$ GeV. Below this cut the non exclusive background was estimated to be about 1/6 with respect to the signal and has been subtracted.

In fig. 6 distributions of exclusive π^+ data are compared with Monte Carlo distributions of events generated in the framework of a SPD model. The data show a nice Q^{-6} distribution and give evidence of the pion pole contribution at low $-t$. The evaluation of the exclusive π^+ cross section is currently under study.

Large single-spin azimuthal asymmetries for exclusive π^+ are expected for a transversely polarised target due to the interference between pole and non pole amplitudes [12]. The size of this asymmetry will strongly depend on the choice of the pion distribution amplitudes. No prediction is at the moment available for longitudinally polarised targets. In this case the asymmetry should arise from the interference between amplitudes with longitudinal and transverse polarisation of the virtual photon [13].

In the case of the HERMES measurement with a longitudinally polarised target, a small transverse target component along the virtual photon direction arise from the non collinearity of the virtual photon with respect to the incident lepton.

Therefore the azimuthal spin asymmetry receives contributions from both transverse and longitudinal target polarisations:

$$\sigma_S \sim [S_\perp \sigma_L + S_\parallel \sigma_{LT}] \cdot A_{UL}^{\sin\phi} \sin\phi$$

where for the HERMES kinematics $S_\perp / S_\parallel \sim 0.17$ on average.

In fig. 7 the single-spin azimuthal asymmetry is shown for both exclusive and semi-inclusive π^+.

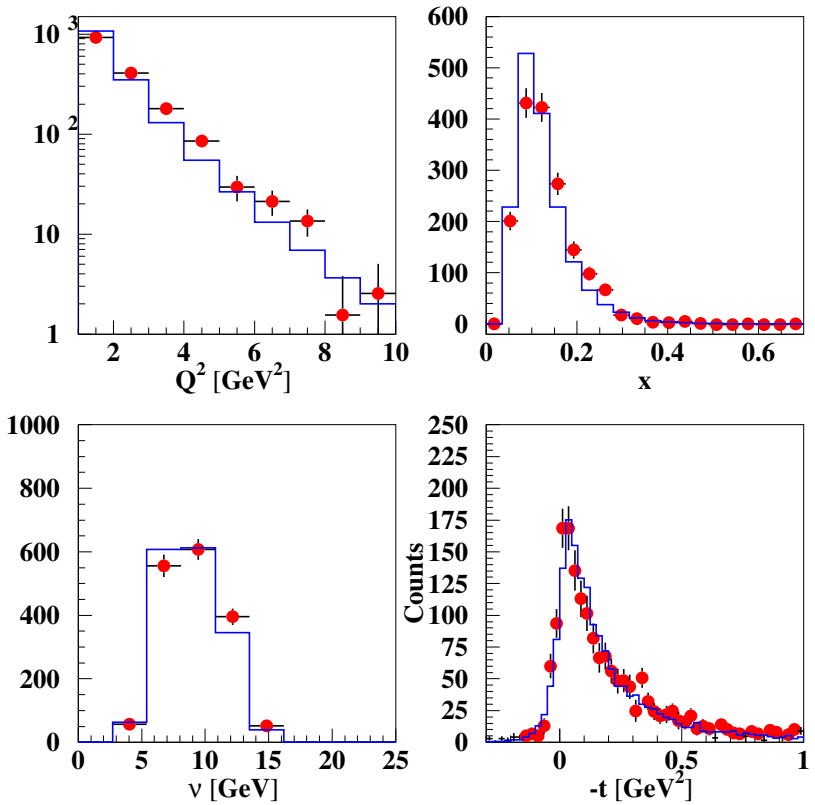

Figure 6. Comparison of exclusive π^+ data distributions with MC distributions based on SPDs.

The asymmetry in the exclusive case is one order of magnitude larger and with opposite sign with respect to the SIDIS one. The $\sin\phi$ moment of the exclusive cross section asymmetry is measured to be $A_{UL}^{sin\phi} = -0.18 \pm 0.05(stat) \pm 0.01(syst)$, while $\sin 2\phi$, $\cos\phi$ and $\cos 2\phi$ moments are compatible with zero. This asymmetry has been found to be insensitive to the M_X cut used in the analysis, supporting the reliability of the background subtraction procedure.

The azimuthal asymmetry for exclusive pions has been also studied as function of the variables x, Q^2 and $-t$. At small x, where the transverse target component is negligible, the size of the asymmetry clearly shows a dominance of the longitudinal target twist-3 component.

4. Single-spin azimuthal asymmetry in DVCS

Deeply Virtual Compton Scattering (DVCS) is the exclusive reaction with the simplest final state where a single photon is produced. As compared to exclusive meson production, DVCS has the advantage that the complication of a meson wave function

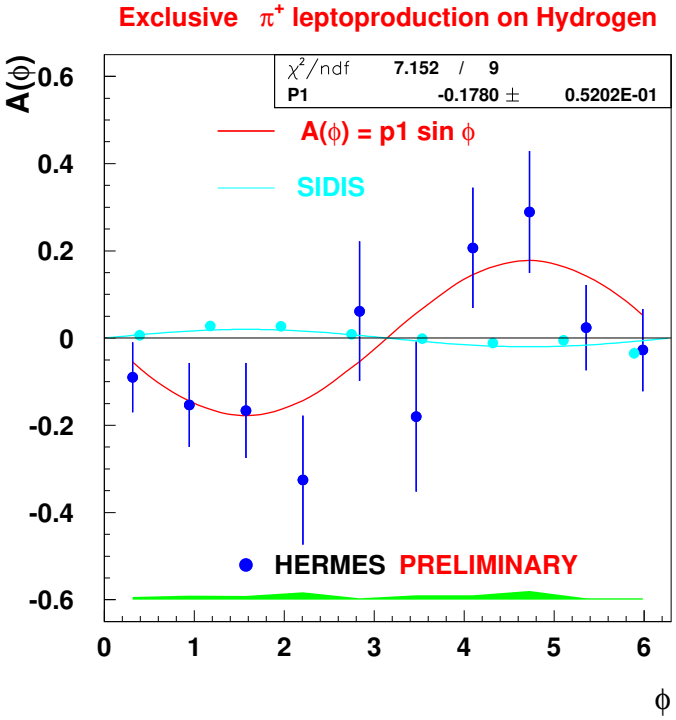

Figure 7. Exclusive π^+ single-spin azimuthal asymmetry. The curve is a $\sin\phi$ fit to the data. The small azimuthal asymmetry close to zero is the SIDIS one.

convoluted with the final state of the target is avoided. However, DVCS has the same final state as the Bethe-Heitler (BH) process where the photon is radiated by the incoming or outgoing lepton. This make the DVCS difficult to isolate due to the large contribution of BH. Therefore at HERMES the single-spin azimuthal asymmetry with respect to the helicity of the beam is used to isolate the interference term of the BH and DVCS processes, providing access to the DVCS contribution. Photons from DVCS and BH processes were identified by the detection of an energy deposition in the calorimeter and preshower detector without any associated track. The recoil proton was not detected and therefore the requirement for exclusivity was ensured by a cut in the M_X missing-mass distribution for the reaction $e^+p \rightarrow e^+\gamma X$. The M_X distribution of this reaction is shown in fig. 8 where a clear signal due to the DVCS and BH processes is seen at M_X around the nucleon mass.

In fig. 9 the azimuthal dependence of the single-spin (beam) azimuthal asymmetry for real photons in the exclusive region of missing mass from 0.4 to 1.7 GeV is shown [14]. Negligible single-spin (beam) asymmetries were observed for higher values of M_X.

The DVCS-BH interference asymmetry shows a clear $\sin\phi$ behaviour and is compared with a SPD prediction, which includes the twist-2 and the twist-3 contributions computed for the average HERMES kinematics [15].

The analyzing power was measured to be $A_{LU}^{\sin\phi}$ = -0.23 ± 0.04 (stat) ± 0.03 (syst) at $\langle x\rangle = 0.11$, $\langle Q^2\rangle = 2.6$ GeV^2 and $\langle -t\rangle = 0.27$ GeV^2.

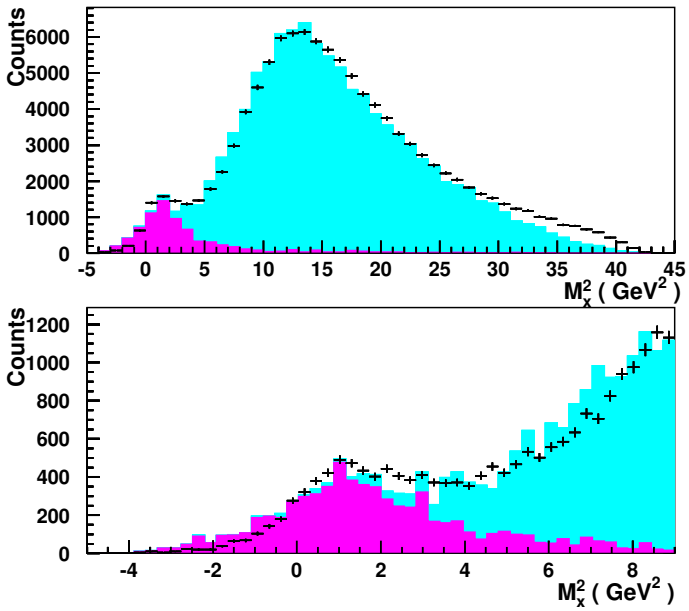

Figure 8. Missing-mass distribution for the reaction $e^+p \to e^+\gamma X$. The enhancement at $M_X^2 \sim 1$ GeV^2 is due to the Bethe-Heitler contribution, while at larger M_X the dominant contribution is coming from fragmentation processes. The dark histogram indicates the expected BH contribution, while the light histogram shows the sum of BH and fragmentation contributions.

The presented DVCS-BH interference results are related to the data collected in 1996 and 1997 with a positron beam. A larger amount of data has already been collected by running the unpolarised target at high density. Also data with an electron beam have been collected. While the beam spin azimuthal asymmetry of a hard exclusive photon depends on the Imaginary Part of the DVCS amplitudes, the beam charge azimuthal asymmetry depends on the Real Part of the DVCS amplitudes. In fig. 10 the projected statistical accuracy for the beam spin asymmetry and for the beam charge asymmetry are shown for an integrated luminosity of 2 fb^{-1} which corresponds to what is expected for one year of data taking. With such an accuracy, a detailed study of both asymmetries as a function of the relevant kinematic variables will be possible.

5. Conclusion and outlook

The first results on semi-inclusive and exclusive single-spin azimuthal asymmetries at HERMES have been presented. The results are obtained from data collected in 96 and 97. Analysis of data collected in 98, 99 and 00 is in progress. In the year 02 and 03, HERMES will run with transversely polarized target. This will

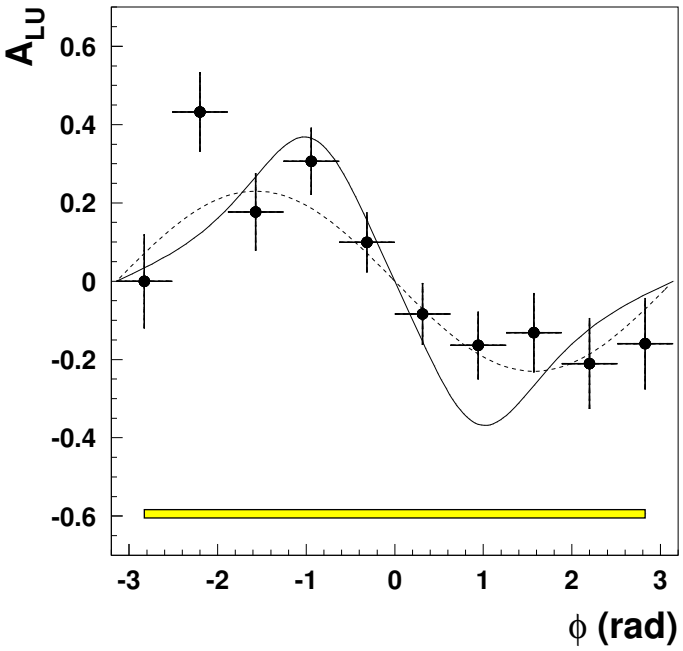

Figure 9. Beam-Spin Azimuthal Asymmetry for the hard electroproduction of photons. The dashed curve represents a $\sin\phi$ dependence with an amplitude of 0.23 while the solid line represents the result of a SPD model calculation.

allow to precisely measure the single-spin (target) azimuthal asymmetries for semi-inclusive and exclusive π^+ which are both expected to be large. High luminosity runs with an unpolarized target are also foreseen for cross section and single-spin (beam) azimuthal asymmetry measurements. In addition, a recoil detector project is under study which will greatly increase the capability of measuring DVCS and exclusive π^0 and η electroproduction. Therefore, after the first but encouraging glimpse, more precise informations on transversity distributions and on SPDs will be collected by HERMES.

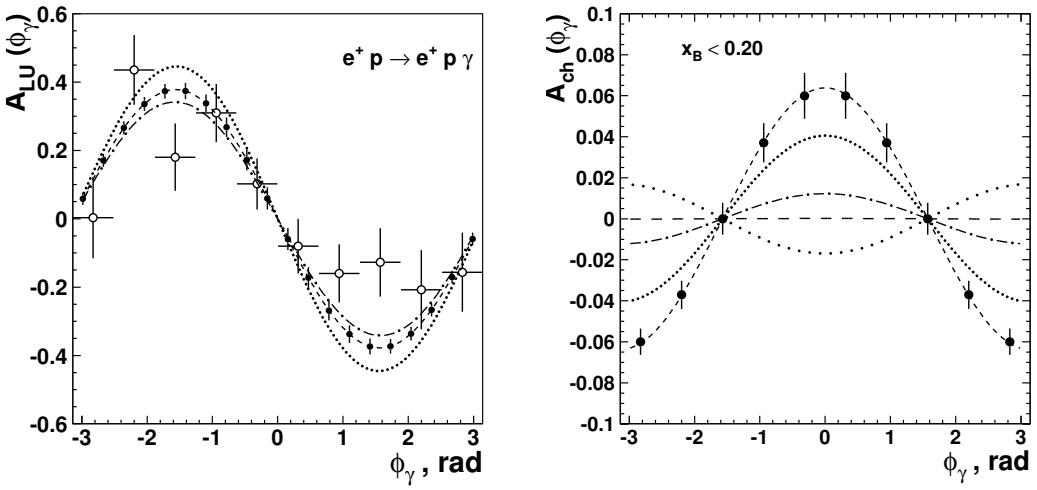

Figure 10. Projected statistical accuracy for the beam spin (A_{LU}) and beam charge (A_{ch}) azimuthal accuracy. Curves are different SPD models. For the beam spin asymmetry the published data (open symbols) are also shown.

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