Abstract

We have analyzed the longitudinally polarized proton target asymmetry data of the Deep Virtual Compton process recently published by the HERMES collaboration in terms of Generalized Parton Distributions. We have fitted these new data in a largely model-independent fashion and the procedure results in numerical constraints on the \( \tilde{H}_{\text{Im}} \) Compton Form Factor. We present its \( t \)- and \( \xi \)- dependencies. We also find improvement on the determination of two other Compton Form Factors, \( H_{\text{Re}} \) and \( H_{\text{Im}} \).

The Deep Virtual Compton Scattering (DVCS) process, i.e. the electroproduction at large virtuality \( Q^2 \) of a real photon off the nucleon, is the most favorable channel to access Generalized Parton Distributions (GPDs). GPDs encode the complex parton (quark and gluon) substructure of the nucleon, not yet fully calculable from the first principles of Quantum Chromo-Dynamics (QCD). GPDs describe, among many other aspects, the (correlated) spatial and momentum distributions of the partons in the nucleon (including polarization degrees of freedom), its quark-antiquark content, they provide a way to access the orbital momentum contribution of the quarks to the nucleon’s spin, etc. We refer the reader to Refs. [1, 2, 3, 4, 5, 6, 7, 8, 9], which contain very detailed and quasi-exhaustive reviews on the GPD formalism and the definitions of some of the variables and notations that will be employed in the following.

We recall that there are, in the QCD leading twist/leading order approximation which is the frame of this study, four independent GPDs which can be accessed in the DVCS process: \( H, E, \tilde{H} \) and \( \tilde{E} \). They correspond to the various spin and helicity orientations of the quark and nucleon in the handbag diagram of Fig. 1.

These four GPDs depend on three variables \( x, \xi \) and \( t \). The quantities \( x + \xi \) and \( x - \xi \) denote the longitudinal momentum fractions of the initial and final quark (or antiquark) respectively, in a frame where the nucleon has a large momentum along a certain direction which defines the longitudinal components. The variable \( t = (p - p')^2 \) is the squared momentum transfer between the initial and final nucleon with \( p \) and \( p' \) as four-momenta respectively. The variable \( \xi \) is
related to the standard Bjorken variable: $\xi \simeq x_B^{2Q^2} \frac{2}{x_B^2}$ in the Bjorken limit as $Q^2 \to \infty$, with $x_B = \frac{Q^2}{2p.q}$ where $q$ is the four-momenta of the virtual photon. Only $\xi$ and $t$ can be determined experimentally in DVCS. Thus, only Compton Form Factors (CFFs), which are weighted integrals of GPDs over $x$ or combinations of GPDs at the line $x = \xi$ and which therefore depend only on the two kinematic variables $\xi$ and $t$, can actually be measured in DVCS experiments. Eight CFFs arise from the decomposition of the DVCS amplitude into real and imaginary parts and, following our notations and definitions introduced in Refs. [10, 11, 12], we call them: $H_{Re}, E_{Re}, \tilde{H}_{Re}, \tilde{E}_{Re}, H_{Im}, E_{Im}, \tilde{H}_{Im}$ and $\tilde{E}_{Im}$. The CFFs with the “Re” index refer to the weighted integrals of GPDs over $x$ and those with the “Im” index refer to the GPDs at the particular point $x = \xi$. We stress that what we call Compton Form Factor does not correspond exactly to the original definition of Ref [13]. In this latter article, CFFs are, up to minus signs and $\pi$ factors, the complex sum of our “Re” and “Im” CFFs.

In Refs. [10, 11, 12], we have developed a largely model-independent fitting procedure which, at a given experimental ($\xi$, $-t$) kinematic point, takes the CFFs as free parameters and extracts them from DVCS experimental observables using the well established DVCS theoretical amplitude [13, 14]. This task is not trivial. Firstly, one has to fit eight parameters from a limited set of data and observables, which leads in general to an under-constrained problem. However, as some observables are in general dominated by a few particular CFFs, one can manage, in some cases, to extract some specific CFFs. Secondly, there is, in addition to the particular DVCS process of direct interest, another mechanism which contributes to the $ep \to e'p'\gamma$ process. This is the Bethe-Heitler (BH) process where the final state photon is radiated by the incoming or scattered electron and not by the nucleon itself. This latter reaction carries no
useful information about GPDs. The BH process interferes with DVCS and in some parts of the phase space has a cross section which dominates the DVCS one. It can therefore mask or “distort” (favorably or unfavorably) the DVCS and GPD signals and it is crucial to properly take it into account. The BH process is however relatively precisely known and calculable given the nucleon form factors.

With our fitting algorithm, we have managed to determine in previous works [10, 11, 12], within average uncertainties of the order of 30%:

- the $H_{\text{Im}}$ and $H_{\text{Re}}$ CFFs, at $< x_B > \approx 0.36$, and for several $t$ values, by fitting [10] the JLab Hall A proton DVCS beam-polarized and unpolarized cross sections [13],

- the $H_{\text{Im}}$ and $\tilde{H}_{\text{Im}}$ CFFs, at $< x_B > \approx 0.35$ and $< x_B > \approx 0.25$, and for several $t$ values, by fitting [12] the JLab CLAS proton DVCS beam-polarized and longitudinally polarized target spin asymmetries [16, 17],

- the $H_{\text{Im}}$ and $H_{\text{Re}}$ CFFs, at $< x_B > \approx 0.09$, and for several $t$ values, by fitting [11] a series (seventeen) of HERMES beam-charge, beam-polarized and transversely polarized target spin asymmetry moments [18, 19].

Now, the HERMES collaboration has recently published [20] two new proton DVCS observables: the single spin asymmetry with a longitudinally polarized proton target and the double spin asymmetry with a polarized positron beam and a longitudinally polarized proton target (the direction of the virtual photon defines the longitudinal axis here). These two independent observables are presented in the form of moments in Ref. [21, 22], denoted as: $A_{UL}^{\sin \phi}$, $A_{UL}^{\sin 2\phi}$, $A_{UL}^{\sin 3\phi}$, $A_{LL}^{\sin \phi}$, $A_{LL}^{\cos \phi}$ and $A_{LL}^{\cos 2\phi}$. In this notation, the first index of the asymmetry $A$ refers to the polarization of the beam (“U” for unpolarized and “L” for longitudinally polarized) and the second one to the polarization of the target (“L” for a longitudinally polarized target). The superscript refers to the harmonic dependence of the asymmetries. $\phi$ is the azimuthal angle between the leptonic and hadronic planes [20, 21].

In this letter, we study what new information these additional observables can bring. It is well known [13, 10, 12] that the longitudinally polarized target spin observable is predominantly sensitive to $\tilde{H}_{\text{Im}}$. We thus expect to extract numerical constraints on this particular CFF for the first time at HERMES kinematics. Our procedure consists in fitting these six new moments in addition to the HERMES other (seventeen) moments previously mentioned, related to the beam-charge, beam-polarized and transversely polarized target spin asymmetries (many of these moments being zero in the leading twist DVCS approximation). We recall that we already fitted in Ref. [11] these seventeen moments but no convergence of the $\tilde{H}_{\text{Im}}$ CFF towards some well-defined domain could be observed (in contrast with the $H_{\text{Im}}$ and $H_{\text{Re}}$ CFFs).

The parameters to be fitted are the CFFs and the function to be minimized is:
\[ \chi^2 = \sum_{i=1}^{n} \frac{(A_{i}^{\text{theo}} - A_{i}^{\text{exp}})^2}{(\delta\sigma_{i}^{\text{exp}})^2} \]  

(1)

where \( i \) runs over all the twenty-three (seventeen + six) HERMES asymmetry moments previously mentioned, \( A_{i}^{\text{theo}} \) is the theoretical asymmetry moment calculated from the sum of the leading twist/leading order DVCS amplitude and of the exact BH amplitude, \( A_{i}^{\text{exp}} \) is the corresponding HERMES experimental value and \( \delta\sigma_{i}^{\text{exp}} \) is its associated experimental error bar. We have used MINUIT and MINOS [22] to carry out the \( \chi^2 \) minimization and to determine the uncertainties on the fitted parameters.

We mentioned earlier that there are in principle eight CFFs appearing in the DVCS process. As in Refs. [10, 11, 12], we have actually considered only seven CFFs as we have set \( \tilde{E}_{\text{Im}} \) to zero, guided by theoretical considerations. The \( \tilde{E} \) GPD is indeed in general associated to the pion pole exchange in the \( t \)-channel whose amplitude is real. We stress that this is essentially the only model assumption in our procedure.

Also, following what we have done and explained in details in Refs. [10, 11, 12], another feature entering our fitting procedure is that we constrain the domain of the fitting parameters (i.e. the CFFs) to be \( \pm 5 \) times a set of “reference” CFFs. Without any bounding, our fits which are in general underconstrained, would not converge. These reference CFFs are the “VGG” CFFs. VGG [14, 5, 23] is a well-known and widely used model which provides an acceptable first approximation of the CFFs, as shown in our previous studies [10, 11, 12] and as will be confirmed furtherdown in the present work. We recall that some GPDs have to satisfy a certain number of normalization constraints. These are all fulfilled by the VGG model. It should be clear that \( \pm 5 \) times the VGG CFFs make up extremely conservative bounds and that this bounding can barely be considered as model-dependent.

Under these largely model-independent conditions, we then obtain the fits, as a function of \( t \), of the six HERMES \( A_{UL} \) and \( A_{LL} \) moments shown in Fig. 2. The thick solid line is the result of the fit of the twenty-three HERMES moments: the seventeen from Refs. [18, 19] (not shown here) and the six from Ref. [20] shown in this figure. Within our leading twist/leading order DVCS framework, only three of the moments in Fig. 2 i.e. \( A_{\sin \phi}^{UL} \), \( A_{0}^{LL} \) and \( A_{\cos \phi}^{LL} \) can be significantly different from zero. The other three moments \( A_{\sin 2\phi}^{UL} \), \( A_{\sin 3\phi}^{UL} \) and \( A_{\cos 2\phi}^{LL} \) are higher twist contributions. The data for the latter two moments are, in general, compatible with zero and therefore quite well fitted by our code. However, the data for the \( A_{\sin 2\phi}^{UL} \) moment are systematically significantly different from zero. This is impossible to achieve within our framework. Out of all our previous studies [10, 11, 12], this is the first observable that we systematically cannot well reproduce with our fitting code. In other words, this is the first significant and systematic DVCS higher twist sign that we encounter. This was of course also noted in the HERMES publication [20]. However, let us mention that, while in Fig. 2 we show the \( t \)-dependence of the \( A_{UL} \) and \( A_{LL} \) moments at (almost) fixed \( < x_B > \), in Ref. [20], the \( x_B \) dependence at (almost) fixed \( -t \) is also shown.
There, it can then be observed that only one $A_{UL}^{\sin 2\phi}$ data point, among four, at an intermediate $<x_B>$ value ($<x_B>=0.084$), is significantly different from zero. This rather “local” deviation is intriguing and could hint that a statistical fluctuation might not be completely out of the question. Otherwise, one has to conceive a non-obvious mechanism which provides such a sharp and local rise of $A_{UL}^{\sin 2\phi}$ at that particular $<x_B>$ value.

**Figure 2:** The six HERMES $A_{UL}$ and $A_{LL}$ moments, as a function of $-t$, which are fitted simultaneously (along with seventeen other moments previously published by HERMES). The solid circles are the data points of Ref. [20]. The thick solid line is the result of our fit which includes all the other seventeen moments of Refs. [18, 19]. The dashed line shows the result of our fit excluding the three $A_{LL}$ moments (i.e. only twenty moments are fitted simultaneously). The dot-dashed line shows the result of our fit excluding also the $A_{UL}^{\sin \phi}$ moment of Ref. [18] (i.e. nineteen moments are fitted simultaneously). The results of our fits are calculated at the experimental bin centres and connected by straight lines for visibility only. The dotted line is the result of the BH alone calculation. The empty crosses are the predictions of the VGG model.

This poor reconstruction of the $A_{UL}^{\sin 2\phi}$ moment being noticed and unexplained, we now focus on the three $A_{UL}^{\sin \phi}$, $A_{LL}^0$, and $A_{LL}^{\cos \phi}$ moments which are “allowed” to be significantly different from zero at leading twist DVCS. We first note in Fig. 2 that $A_{LL}^{\cos \phi}$ is very small although it is leading twist. It is indeed largely dominated by BH which gives this moment essentially equal to zero. Now, turning to the two other leading twist moments, $A_{UL}^{\sin \phi}$ and $A_{LL}^0$, which experimentally do turn out to be significantly different from zero, we see that
they are well fitted for three out of four $t$-values. Indeed, our fit (thick solid line) misses the third $t$ point, i.e. at $< -t >= 0.201$ GeV$^2$, for both observables. Once again, a strong “local” discontinuity occurs for $A_{UL}^0$, being negative for this particular value $t$ value while being positive for the other three $t$ values. This might point to another local and singular statistical effect. The dashed line in Fig. 2 shows the result of our fit if we remove the $A_{LL}$ moments. We then note that the fit of $A_{UL}^{\sin \phi}$ is improved.

Still, the dashed line is not passing exactly through the central value of $A_{UL}^{\sin \phi}$ at $< -t >= 0.201$ GeV$^2$. We recall that we fit simultaneously twenty-three moments and not only the $A_{UL}$ and $A_{LL}$ moments. This means that another observable must outweigh $A_{UL}^{\sin \phi}$ and push the fit away from the $A_{UL}^{\sin \phi}$ data point at that particular $t$ value. We will identify this other observable furtherdown and will then describe the dot-dashed curve which does correctly fit all $A_{UL}^{\sin \phi}$ data points.

In Fig. 2, the dotted curve shows the result of the calculation with only the BH contribution. It is essentially zero for all $A_{UL}$ and $A_{LL}$ moments but $A_{UL}^0$. The dotted curve shows that the main contribution to this latter moment comes basically from BH alone and that the DVCS contribution to this observable is very small. The empty crosses in Fig. 2 show the VGG prediction which, except for the puzzling higher twist $A_{UL}^{\sin 2\phi}$, gives a relatively good overall description of the data.

We now show in Fig. 3 six of the other seventeen observables that we simultaneously fit with the $A_{UL}$ and $A_{LL}$ moments of Fig. 2. We recall that this set of seventeen moments was studied in detail in Ref. [11]. The six moments displayed in Fig. 3 i.e. $A_{(C)}$, $A_{(C)}^\cos \phi$, $A_2$, $A_{(Uy)}^\sin \phi$, $A_{(Ux)}^\sin \phi$ and $A_{(LU)}^\sin \phi$ are the moments which can be significantly different from zero at leading twist DVCS, out of the seventeen published by HERMES in Refs. [18, 19]. These observables actually originate from two independent analyses (although they bear on the same data set). Ref. [18] has extracted the $A_{(C)}$ and $A_{(UT)}$ asymmetries while Ref. [19] have extracted the $A_{(LU)}$ asymmetries (as well as, simultaneously, the $A_{(C)}$ asymmetries also). The two analyses have different binnings and thus slightly different central $-t$ (and $x_B$) values. As was explained in details in Ref. [11], in order to be able to fit simultaneously all observables, we have considered that all data were taken at the four $-t$ points of Ref. [18]. These four $-t$ points are actually the same as in Ref. [20] (and thus as in Fig. 2). The actual fitted data are therefore the solid circles in Fig. 3. A slight uncertainty for the $A_{(LU)}$ asymmetries is thus introduced since they are not calculated at the exact kinematics at which they were measured. Given the uncertainties on our final results, which we will present shortly, we consider this effect as negligible.

Similar to Fig. 2, the thick solid line in Fig. 3 shows the result of our fit when all twenty-three HERMES moments are included in the fit, i.e. with the new $A_{UL}$ and $A_{LL}$ moments. The thin solid line in Fig. 3 shows the results that we previously published in Ref. [11], i.e. without the new $A_{UL}$ and $A_{LL}$ moments. Except for $A_{(Ux,1)}^\sin \phi$, the thick and solid lines are essentially superimposed, which shows that the introduction of the $A_{UL}$ and $A_{LL}$ moments in our fit did not
Figure 3: Six out of seventeen moments determined at HERMES, other than those of Fig. 2, which are fitted simultaneously in this work as a function of $-t$. For the two $A_{C\{C\}}$ asymmetry moments, the solid circles show the HERMES data of Refs. 18, 19 and the open circles show the HERMES data of Ref. 19. For the three $A_{U\{x,y\}}$ asymmetry moments, the solid circles show the HERMES data of Refs. 18, 19. For the $A_{LU}$ asymmetry moment, the open circles show the HERMES data of Ref. 19 and the solid circles show these SAME data offset to the kinematics of Ref. 18 (and of Ref. 20), so as to fit all (twenty-three) moments simultaneously at the same kinematics. In other words, the solid circles in all panels show the data point which have actually been fitted. The thick solid line is the result of our fit including all twenty-three moments. The thin solid line is the result of our fit, previously published in Ref. 11, i.e. excluding the three $A_{UL}$ and the three $A_{LL}$ moments (of Fig. 2), i.e. seventeen moments have been fitted. In most cases, the thin solid line overlaps with the thick solid line and cannot be distinguished. The dashed line (also barely visible) shows the result of our fit excluding the three $A_{UL}$ moments (i.e. twenty moments are fitted). The dot-dashed line (mostly visible on the $A_{Ux}^{\sin \phi}$ panel) shows the result of our fit excluding in addition the $A_{Ux}^{\sin \phi}$ moment of Ref. 18 (i.e. nineteen moments are fitted). The results of our fits are calculated at the experimental bin centres and connected by straight lines for visibility only. The empty crosses are the predictions of the VGG model.
in general strongly affect our previous results, as expected. However, there is a striking difference for $A_{\{Ux,1\}}^{\sin \varphi}$ at the third $t$ point, i.e. at $-t > 0.201$ GeV$^2$. This is precisely the $-t$ value for which we previously observed some problem for $A_{UL}^{\sin \varphi}$ and $A_{LL}^0$ (see Fig. 2). Within our fitting algorithm (we recall, based on the leading twist DVCS assumption), it thus doesn’t appear possible to fit simultaneously these three asymmetry moments, i.e. $A_{\{Ux,1\}}^{\sin \varphi}$, $A_{UL}^{\sin \varphi}$ and $A_{LL}^0$. Indeed, the thin solid line in Fig. 3 (i.e. the fit without the $A_{UL}$ and $A_{LL}$ moments) perfectly fits $A_{\{Ux,1\}}^{\sin \varphi}$ while the thick solid line in Figs. 2 and 3 (i.e. the fit with the $A_{UL}$ and $A_{LL}$ moments included) misses both $A_{\{Ux,1\}}^{\sin \varphi}$ and $A_{UL}^{\sin \varphi}$. In other words, including $A_{UL}^{\sin \varphi}$ in the data to be fitted spoils the fit of $A_{\{Ux,1\}}^{\sin \varphi}$ (at $-t > 0.201$ GeV$^2$). The uncertainties of $A_{\{Ux,1\}}^{\sin \varphi}$ and $A_{UL}^{\sin \varphi}$ at $-t > 0.201$ GeV$^2$ are respectively $\approx 60\%$ and $\approx 40\%$. Thus, the minimization procedure finds some sort of “intermediate” solution in order to accommodate both data points when both moments, $A_{\{Ux,1\}}^{\sin \varphi}$ and $A_{UL}^{\sin \varphi}$, are included in the fit (thick solid line in Figs. 2 and 3).

In order to better understand this issue, we have removed the $A_{\{Ux,1\}}^{\sin \varphi}$ and $A_{LL}$ moments of our fit which seem to pose problems. The result of this fit is the dot-dashed curve in Figs. 2 and 3 $A_{UL}^{\sin \varphi}$ is now very well fitted, in particular the third $t$ point at $-t > 0.201$ GeV$^2$. Of course, since $A_{\{Ux,1\}}^{\sin \varphi}$ was not included in the fit, it is not particularly well fitted, in particular the problematic third $t$ point at $-t > 0.201$ GeV$^2$ in Fig. 3. To summarize this discussion, the inclusion of $A_{\{Ux,1\}}^{\sin \varphi}$ in the fit seems to spoil the fit of $A_{\{Ux,1\}}^{\sin \varphi}$ and, oppositely, the inclusion of $A_{UL}^{\sin \varphi}$ in the fit seems to spoil the fit of $A_{UL}^{\sin \varphi}$.

As we will see shortly, the precise value of $A_{UL}^{\sin \varphi}$ is going to directly impact the value of the $H_{im}$ CFF. It would therefore be important to clarify which one of the two fitting curves, i.e. the thick solid one or the dot-dashed one in Figs. 2 and 3, one should actually consider. We cannot decide alone which data point, between $A_{\{Ux,1\}}^{\sin \varphi}$ and $A_{UL}^{\sin \varphi}$ (at $-t > 0.201$ GeV$^2$), is the “most correct”. However, we can notice that the VGG prediction (the empty crosses in Figs. 2 and 3) which, in general, gives a decent description of the data, seems to favor $A_{\{Ux,1\}}^{\sin \varphi}$ values close to zero, which differs significantly with the experimental data point at $-t > 0.201$ GeV$^2$.

Now that we have compared our fit curves to the data, let us examine the values of the fitted CFFs which come out of the minimization procedure. Three CFFs $H_{Re}$, $H_{Im}$ and $\tilde{H}_{im}$ come out of our fitting procedure with finite MINOS uncertainties and stable central values. The other four fitted CFFs did not converge to some well defined value or domain: either their central value reached the boundaries of the allowed domain of variation ($\pm 5$ times the VGG value) or MINOS could not reach the $\chi^2+1$ value and thus we could not well define the associated uncertainty. The explanation for which some particular CFFs do converge and do come out of the fits within well defined and delimited domains is that some observables are, for dynamical or kinematical reasons, particularly
sensitive to some specific CFFs. For instance, it is well established [10, 13, 21] that DVCS charge asymmetries are in general mostly sensitive to $H_{Re}$, beam single spin asymmetries to $H_{Im}$ and, particularly related to the present work, longitudinally polarized target single spin asymmetries to $\tilde{H}_{Im}$.

The central values for the $H_{Re}$ and $H_{Im}$ CFFs that we obtain in this work, are almost unchanged compared to the ones we obtained in Ref. [11], where the six $A_{UL}$ and $A_{LL}$ moments were not included. The important difference is that now the $\tilde{H}_{Im}$ CFF does converge to a well-defined value. This could of course be anticipated given the previously mentioned sensitivity of the $A_{UL}$ moments to this particular CFF. We first discuss the $\tilde{H}_{Im}$ CFF and will come back a few paragraphs below to the $H_{Re}$ and $H_{Im}$ CFFs and see the improvement gained in their determination due to the introduction of the $A_{UL}$ and $A_{LL}$ moments in the fit.

![Figure 4](image)

Figure 4: The $t$-dependence of the $\tilde{H}_{Im}$ CFF, extracted from our fits (left: at HERMES kinematics; right: at CLAS kinematics). The empty squares (circles) show our results when the boundary values of the domain over which the CFFs are allowed to vary is 5 (3) times the VGG reference values. In the left panel, at $< -t > = 0.201$ GeV$^2$, the set of points with the dashed error bars are the results of our fit when all twenty-three moments are included. The set of points with the solid error bars are the results of our fit when $A_{UL}$ and $A_{LL}$ moments are excluded from the fit (i.e. only nineteen moments are fitted). The empty crosses indicate the VGG prediction.

We show in the left panel of Fig. 4 the resulting values of $\tilde{H}_{Im}$ that we obtain and which are therefore an original result. We made the fits for the four $t$ values of Figs. 2 and 3. However, we display in Fig. 4 $\tilde{H}_{Im}$ for only the three largest $< -t >$ values, i.e. $< -t > = 0.094, 0.201$ and $0.408$ GeV$^2$. Indeed, the MINOS uncertainties on $\tilde{H}_{Im}$ were at the level of 100% for the smallest $< -t >$ point. We note that at this (very small) $t$ value, $A_{UL}^{sin\phi} = -0.008 \pm 0.051 \pm 0.012$, i.e. it is close to zero with, consequently, a very important uncertainty. In Fig. 4
following our convention used in Ref. [12], the empty squares show our results for \( \tilde{H}_{\text{Im}} \) when the CFFs are limited to vary within \( \pm 5 \) times the VGG reference values while the open circles show these results for boundary values equal to \( \pm 3 \) times these same VGG reference values. The empty square and circle symbols have been slightly offset from the central \( t \) values, left and right respectively, for sake of visibility. The uncertainties that we obtain on our fitted CFFs have in general two origins. One of course is related to the statistical precision of the data that are fitted. The other one stems from the correlation between the fitted parameters. This latter cause of uncertainty reflects the potential influence of all the other CFFs. We recall that, in order to be as model-independent as possible, the essence of our approach is essentially (i.e. except for \( \tilde{E}_{\text{Im}} \)) to make no assumption on the value of any of the CFFs. Then, of course, the smaller the domain of variation allowed for the CFFs (i.e. \( \pm 3 \) times compared to \( \pm 5 \) times the VGG reference values), the smaller the error bars on the “convergent” CFFs due to this effect. This is what we observed in our previous studies [10, 11, 12].

We can note in Fig. 4 that there is not a strong difference between the values of the relative error bars of the two cases considered here, i.e. \( \pm 3 \) times and \( \pm 5 \) times the VGG reference values. This is a sign that these error bars have mostly a statistical origin (we note that three out of the four \( A_{\sin} \{ U_x, I \} \) that we fit have an experimental uncertainty of more than 80%, see Fig. 2). This difference will be more pronounced when we will look at the \( H_{\text{Re}} \) CFF further down.

At \( < -t > = 0.201 \text{ GeV}^2 \), we display two sets of values in the left panel of Fig. 4. The values with the dashed error bars correspond to the fit when \( A_{\{ U_x, I \}}^{\sin \phi} \) (and the six \( A_{U_L} \) and \( A_{L_L} \) moments) is included. We saw in Figs. 2 and 3 (thick solid line) that then \( A_{U_L}^{\sin \phi} \) is underestimated at that particular \( t \) value. As a consequence, it can be deduced that in this case \( \tilde{H}_{\text{Im}} \) will also be underestimated. Hence the value of \( \tilde{H}_{\text{Im}} \) gets close to zero in Fig. 4 at \( < -t > = 0.201 \text{ GeV}^2 \) (empty square and circle with dashed error bars). Now, if one excludes \( A_{\{ U_x, I \}}^{\sin \phi} \) (and the three \( A_{L_L} \) moments) from the fit, this yields, as we saw, the dot-dashed curves in Figs. 2 and 3. \( A_{U_L}^{\sin \phi} \) is then correctly fitted and, as a consequence, \( \tilde{H}_{\text{Im}} \) becomes larger. In Fig. 4 this case corresponds to the empty square and circle points with the solid line error bars. We have a couple of (disputable) arguments which tend to make us think that this latter fit is more trustworthy: firstly, the relative uncertainty on \( A_{U_L}^{\sin \phi} \) is a bit less than on \( A_{U_x}^{\sin \phi} \) tending to give more credit to the former moment and, secondly, as we mentioned earlier, the former moment is more consistent with the VGG predictions. Additionally, the sort of structure in \( A_{U_x}^{\sin \phi} \) with some local trend to rise at \( < -t >= 0.201 \text{ GeV}^2 \) is not obvious to explain in a GPD model. We nevertheless show both results in Fig. 4 with, thus, a leaning for the solid line error bar points. Except for the kinematic point at \( < -t > = 0.201 \text{ GeV}^2 \) that we just discussed, the central values of the fitted \( \tilde{H}_{\text{Im}} \) CFFs are in very good agreement with or without the \( A_{U_x}^{\sin \phi} \) and \( A_{L_L} \) moments included in the fit. We therefore don’t show the dashed error bars points for the other \( t \) values.

In the right panel of Fig. 4, we have displayed the values of \( \tilde{H}_{\text{Im}} \) that we
extracted in a previous work \cite{12} from the simultaneous fit of the DVCS longitudinally polarized target single spin asymmetries and the beam single spin asymmetries measured by the CLAS collaboration \cite{16, 17}, i.e. at larger $x_B$. We thus obtain, for the first time, an $x_B$- (or $\xi$-) dependence of $\tilde{H}_{\text{Im}}$. Given the relatively large error bars that we have obtained, it is difficult to draw clearcut conclusions. Nevertheless, considering for the HERMES case only the points with the solid error bars in Fig. 4 we observe some similar trends for the $t$-dependence between the HERMES and CLAS kinematics. If one focuses only on the central values, $\tilde{H}_{\text{Im}}$ tends to go to zero as $-t$ goes to zero. Then, some maximum seems to show for $-t$ between 0.2 and 0.3 GeV$^2$ before a trend to decrease again as $| -t |$ increases. Considering the rather large uncertainties, a flat $t$-dependence cannot be excluded either. In any case, there doesn’t seem to be any strong $t$-dependence for $\tilde{H}_{\text{Im}}$ (in contrast to standard proton-electromagnetic-form factors).

The $x_B$ dependence doesn’t appear to be very strong either. The central values of $H_{\text{Im}}$ tend to show a slow decrease between CLAS and HERMES kinematics. This is corroborated by the VGG predictions (empty crosses in Fig. 4) which show little variation of $H_{\text{Im}}$ between the two $x_B$ values. This is in contrast to $H_{\text{Im}}$ which, at fixed $t$, tends to show some rising behavior as $x_B$ decreases \cite{12}. In the comparison with the VGG model, regarding the $t$-dependence, we however note that there is no decrease of $H_{\text{Im}}$ as $-t$ goes to zero. This difference of behavior as $-t$ goes to zero between the fitted $\tilde{H}_{\text{Im}}$ and the VGG prediction can actually be inferred from Fig. 2 where it can be seen, in the $A_{UL}^{\sin \phi}$ panel, that the empty crosses overestimate (in absolute value) the data at small $| -t |$. This explains that the VGG $H_{\text{Im}}$ is also overestimated at small $| -t |$ compared to the fitted $\tilde{H}_{\text{Im}}$. As a consequence, the VGG $H_{\text{Im}}$ does not show the fall-off trend as $-t$ goes to zero.

The $t$-dependence of GPDs can be interpreted as a reflection of the spatial distribution of some charge \cite{24, 25, 26}.Physically, the smoother $t$-dependence of $\tilde{H}_{\text{Im}}$ compared to $H_{\text{Im}}$ could then suggest that the axial charge has a more narrow distribution than the nucleon than the electromagnetic charge.

Finally, we show in Fig. 5 how the $H_{\text{Re}}$ and $H_{\text{Im}}$ CFFs have been affected by the introduction of the $A_{UL}$ and $A_{LL}$ moments in the fit. The empty squares with the dashed error bars are the results that we published in Ref. \cite{11}, i.e. without the new $A_{UL}$ and $A_{LL}$ moments in the fit. The empty squares with the solid line error bars are the results for the $H_{\text{Re}}$ and $H_{\text{Im}}$ CFFs that we obtain in the present work, i.e. with the addition of the $A_{UL}$ in the fit (but without the $A_{UL}^{\sin \phi}$ and $A_{LL}$ moments as we discussed earlier). The agreement between the “dashed error bar” points and the “solid line error bars” points is in general very good for both CFFs. There is almost no difference for the $H_{\text{Im}}$ CFF besides some reduction in the error bar (most noticeable at the largest $< -t >$ value). The reduction of the error bar is more significant and systematic for the $H_{\text{Re}}$ CFF. For this latter CFF, we also note a significant change at $< -t > = 0.201$ GeV$^2$, i.e. a lowering of the central value (which is though still compatible with the “dashed” error bar of our previous study). In Fig. 5 we also show the VGG
Figure 5: The $t$-dependence of the $H_{\text{Im}}$ (left) and $H_{\text{Re}}$ (right) CFFs, extracted from our fits. The empty squares with the dashed error bars are the results of Ref. [11], i.e. without the new $A_{UL}$ and $A_{LL}$ moments in the fit (with boundary values equal to 5 times the VGG reference values). The empty squares and circles with the solid line error bars are the results of the present work, i.e. with the additional moments of Ref. [20] in the fit (though without the $A_{(Ux,I)}^{\sin \phi}$ and $A_{LL}$ moments, as discussed in the text). The squares (circles) correspond to boundary values 5 (3) times the VGG reference values. The empty crosses indicate the VGG prediction. The solid curves show the results of the model-based fit of Ref. [27].

predictions (empty crosses) and the result of the model-based fit of Ref. [27] (solid curve) which was discussed in Ref. [11]. It is seen that both VGG and the model-based fit of Ref. [11] overestimate our fitted values for $H_{\text{Re}}$ while showing a good agreement for $H_{\text{Im}}$.

To summarize this work, we have analyzed, in the leading twist/leading order handbag diagram and GPD framework, the new longitudinally polarized target asymmetry data of the DVCS process, recently released by the HERMES collaboration [20, 21]. We have used a largely model-independent fitter code, which has been introduced and used successfully in several previous analyses [10, 11, 12], to fit these new data (in addition to other DVCS observables previously published by the HERMES collaboration). We have met difficulties in fitting the experimentally large $A_{UL}^{\sin 2\phi}$ moments which are expected to be a higher twist effect. It thus cannot be described and explained within our fitting framework. It should, however, be noted that this large higher-twist effect is very local as it seems to stem from only one out of four $x_B$ values. We have also met a difficulty in fitting simultaneously the $A_{UL}^{\sin \phi}$ and $A_{(Ux,I)}^{\sin \phi}$ moments at one particular $< -t >$ point ($< -t >= 0.201 \text{ GeV}^2$). This inconsistency, once again within our leading twist DVCS formalism assumption, seems to be corroborated by the VGG model which is in good agreement with the $A_{UL}^{\sin \phi}$ moment but not with the $A_{(Ux,I)}^{\sin \phi}$ moment. We note that, in the comparison with the twenty-
three independent moments measured by HERMES, the VGG model gives a reasonable overall description of the data.

These caveats being noted, our analysis has led for the first time to some numerical constraints on the $\tilde{H}_{\text{Im}}$ CFF at HERMES energies, with well-defined and stable error bars and central values. Using a previous work on CLAS data, we have presented the $\xi$–dependence of the $\tilde{H}_{\text{Im}}$ CFF. It has then been observed that $\tilde{H}_{\text{Im}}$ exhibits the same peculiar $t$–dependence at both energies, i.e. a rather flat $t$-slope with, possibly, a trend to decrease as $-t$ tends towards zero. The $\xi$–dependence is also very shallow with a slight decrease of $\tilde{H}_{\text{Im}}$ between the CLAS and HERMES kinematics. In addition, the results on the other $H_{\text{Re}}$ and $H_{\text{Im}}$ CFFs have also been improved with respect to our previous study \cite{11}.

We are very thankful to Drs D. Mahon, M. Murray, W.-D. Nowak, I. Lehmann and M. Vanderhaeghen for very useful discussions which have enriched this study. This work was supported in part by the French ”Nucleon GDR” no. 3034, the French Agence Nationale pour la Recherche Contract no. ANR-07-BLAN-0338 and the EU FP7 Integrating Activity HadronPhysics2, in particular the Joint Research Activity HardEx.

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