Extraction of the Skewing factor from the DIS/DVCS ratio.

L. Favart[a], M.V.T. Machado[b] and L. Schoeffel[c]

[a] I.I.H.E., Université Libre de Bruxelles, 1050 Brussels, Belgium

[b] High Energy Physics Phenomenology Group, GFPAE, IF-UFRGS
Caixa Postal 15051, CEP 91501-970, Porto Alegre, RS, Brazil

[c] CE Saclay, DAPNIA-SPP, 91191, Gif-sur-Yvette, France

Abstract

The skewing factor, defined as the ratio of the imaginary parts of the amplitudes $Im\,\mathcal{A}(\gamma^*\,p \to \gamma^*\,p)/Im\,\mathcal{A}(\gamma^*\,p \to \gamma\,p)$ is extracted for the first time from the data using recent Deeply Virtual Compton Scattering (DVCS) and the inclusive inelastic cross section measurements at DESY-HERA. The results values are compared to theoretical predictions for NLO QCD and the colour dipole approach.

Introduction

It is well known that the cross section of hard scattering processes can be described as the convolution of parton distributions (PDFs) and the cross sections of hard subprocesses computed at parton level using perturbative QCD. The usual PDFs, obtained from inclusive experimental data, is the diagonal element of an operator in the Wilson operator product expansion (OPE). On the other hand, there is a set of exclusive reactions which are described by the off-diagonal elements of the density matrix, where the momentum, helicity or charge of the outgoing target are not the same as those of the corresponding incident particle. Examples of such reactions are the virtual photon Compton scattering (DVCS) ($\gamma^*p \to \gamma p$) and the vector meson electroproduction ($\gamma^*p \to Vp$). In these cases, the difference with the inclusive case is the longitudinal components of the incoming and outgoing

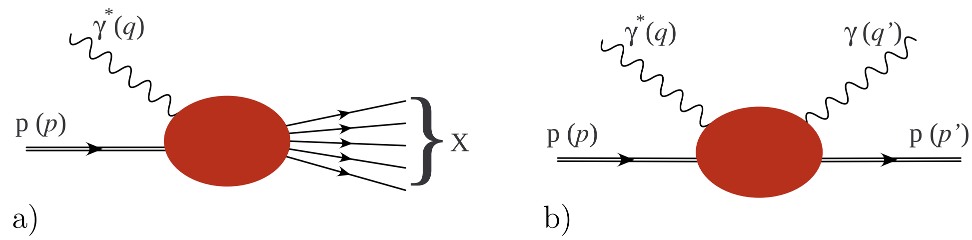

Figure 1: Amplitude level diagrams for DIS (a) and DVCS (b)

proton momentum, which depend on the photon virtuality Q^2 and the $\gamma^* p$ center of mass energy W.

Precision data are becoming available for hard scattering processes whose description requires knowledge of these off-diagonal (or skewed) parton distributions. The exclusive diffractive DVCS process at large Q^2 provides a comparatively clean procedure for extracting information on the gluons within the proton in a non-forward kinematic case. In recent years the study of Deep Inelastic lepton-proton Scattering (DIS) has produced detailed information of the proton structure in terms of Parton Distribution Functions (PDFs). The optical theorem states that the leading DIS process of a single virtual photon exchange can be viewed as identical to the forward elastic scattering of a virtual photon from the proton. This scattering, known as the forward Compton scattering process, is the same as a DIS process (see Fig. 1-a) with its mirrored reaction and relates the total cross section $\sigma_{tot}(\gamma^* p \to X)$ with the imaginary part of the forward amplitude $Im\, A(\gamma^* p \to \gamma^* p)$.

The forward Compton scattering $\gamma^*(q)\, p(p) \to \gamma^*(q)\, p(p)$ can be generalized to the non forward case (at non-zero angles): $\gamma^*(q)\, p(p) \to \gamma^{(*)}(q_2)\, p(p_2)$ with $q_2 \neq q$ and $p_2 \neq p$ and being experimentally accessible through the so called Deeply Virtual Compton Scattering (DVCS) process, where a real photon is observed in the final state (see Fig. 1-b). In analogy with DIS which relates the imaginary part of the forward Compton amplitude and PDFs, in the DVCS process parton distributions are also used to parameterise the non-perturbative part of the interaction in the non-forward region. In this last case, the distributions have to be calculated in terms of non-diagonal, rather than diagonal, PDFs. They are commonly called Generalised Parton Distributions (GPDs). They reduce to the ordinary PDFs in the limit of zero skewedness, i.e., the forward limit.

Let us first summarize the main theoretical approaches describing the DVCS process. From the perturbative QCD point of view, GPDs have been studied extensively and incorporate the partonic and distributional behavior. They are two-parton correlation functions that allow accessing parton correlations within hadrons. For fixed skewedness, they are continuous functions and cover two distinct regions, the DGLAP and the ERBL regions, in which their evolution with the hard scale is driven by the corresponding evolution equations. Moreover, the Lorentz structure of the GPDs implies a polynomiality condition; namely, their $(n-1)$-th moments are polynomials in the square of the skewedness of degree smaller than $n/2$. The most promising approach for GPD parameterisations relies on setting them equal to the forward PDFs using a forward model with suitably symmetrized input GPDs in the ERBL region constructed in order to satisfy polynomiality for the first two momenta [7]. These theoretical studies reproduce satisfactorily the main features of DVCS data [1]. On the other hand, a simple and intuitive high energy formalism has recently been used to describe DVCS [9]. It is given by a colour dipole picture, which allows extending in the studies of saturation physics at low virtualities of the incoming photon. This is an advantage in comparison with the pQCD formalism which is limited by the initial scale for QCD evolution to the order of $Q_0 \gtrsim 1$ GeV. Additionally, the roles played by QCD evolution and skewing effects have been recently shown in the scope of this formalism. The off-diagonal effect has been investigated through a simple phenomenological parameterisation. The overall picture is in good agreement with the experimental data [11].

In this work, we will address the question of the extraction of the skewing correction using the available data on DIS and DVCS. This can be performed by computing the ratio of the imaginary parts of the amplitudes for these reactions. The skewing factor R will depend on the experimental measurements and therefore possess a small degree of model dependence. We therefore have the attractive possibility in determining its dependence upon Q^2 virtuality and upon W energy. This knowledge will enable us to gain insight into the skewedness correction to the non-forward observables. Namely, the non-forward cross section and distributions can be easily obtained from the forward ones by simply multiplying them by the skewing factor. This has direct implications in computing the exclusive meson and heavy boson production via the forward scattering amplitude, which is better constrained from the inclusive measurements.

The paper is organized as follows; in the next section, the skewing factor R is defined and extracted from experimental DESY-HERA results on DIS and DVCS. In section 2 we perform a comparison of the skewing factor with two different theoretical approaches, the perturbative NLO QCD calculation and the colour dipole formalism. A qualitative analysis of the extracted skewing factor is then performed in a colour dipole approach. In the last section we summarize the main results and discussions.

1 Definition and extraction of the skewing factor R

Lets define a basic quantity giving an overall measurement of the skewing properties, which includes both the non-forward kinematics and the non-diagonal effects. Namely, we set the ratio between the imaginary parts of the DIS and DVCS (forward) scattering amplitudes at zero momentum transfer:

$$R \equiv \frac{Im\,\mathcal{A}\,(\gamma^* + p \to \gamma^* + p)\Big|_{t=0}}{Im\,\mathcal{A}\,(\gamma^* + p \to \gamma + p)\Big|_{t=0}}\;, \tag{1}$$

where t is the square of the four-momentum exchanged at the proton vertex.

The scattering amplitude for the DIS process can be directly obtained from the DIS cross section and experimentally measured at DESY-HERA, that is $Im\,\mathcal{A}(\gamma^* p \to \gamma^* p) \sim \sigma_{tot}(\gamma^* p \to X)$. In fact, the DIS amplitude can be written down using the usual pQCD fits for the proton structure function, $\sigma_{tot}^{\gamma^* p} = (4\pi^2\alpha/Q^2)\, F_2^p(x, Q^2)$. The DVCS scattering amplitude can be obtained from the recent measurements on the Deeply Virtual Compton Scattering cross section. In this case, the t dependence of the amplitude can be assumed to be factorised out and parameterised as an exponential,

$\propto \exp(-b|t|)$, and the total DVCS cross section can be related to the corresponding amplitude at $t = 0$; namely,

$$\sigma(\gamma^* p \to \gamma p) = \frac{\left[Im\, \mathcal{A}\,(\gamma^* p \to \gamma p)\Big|_{t=0} \right]^2}{16\pi\, b}\,, \tag{2}$$

where b is the t slope parameter referred to above. The expression above can be corrected by taking into account the contribution from the real part of the amplitude by multiplying Eq. (2) by a factor $(1 + \eta^2)$, where η is the ratio of the real to imaginary part of the DVCS amplitude. The typical contribution for the kinematic window available at HERA is of the order of 20 %. In particular, to a good approximation, η can be calculated using dispersion relations to $\eta \simeq \tan(\pi\lambda/2)$, where $\lambda = \lambda(Q^2)$ is the effective power of the Bjorken x dependence of the imaginary part of the amplitude. For an estimate of the real part contribution we use the effective power for the inclusive deep inelastic reaction taken from Ref. [3].

Considering the calculation discussed above, we can rewrite the skewing factor as a function of the total cross sections for DIS and DVCS. The factor reads as,

$$R = \frac{\sigma(\gamma^* p \to X)\,\sqrt{(1+\eta^2)}}{4\,\sqrt{\pi b\, \sigma(\gamma^* p \to \gamma p)}} = \frac{\sqrt{\pi^3}\,\alpha}{Q^2}\, \frac{F_2^p(x,Q^2)\,\sqrt{(1+\eta^2)}}{\sqrt{b\,\sigma(\gamma^* p \to \gamma p)}}\,. \tag{3}$$

Main theoretical uncertainties come from the b slope and from the estimate of the real part contribution. In our further calculation, one uses the b value extracted from the recent measurements of the t-dependence of DVCS data.

To extract the factor R factor, Eq. (3), we use recent DVCS measurements at HERA [1, 2] and the DIS cross cross section is obtained using the pQCD fits of the F_2^p structure function from Ref. [4]. The factor R is shown as a function of Q^2 in Fig. 2 and as a function of energy W in Fig. 3. The corresponding values are given in tables 1 and 2. The inner error bars represent the statistical error. The full error bars is the quadrature sum of the statistical, systematic and normalisation (precision of the b measurement of H1) uncertainties[1]. A Q^2 dependence is observed, decreasing from $R \simeq 0.7$

[1]important contribution to systematic effects in the H1 measurement are not considered in the ZEUS measurement (e.g. the error on the Bethe-Heitler subtraction which dominates the full systematic error at large W values)

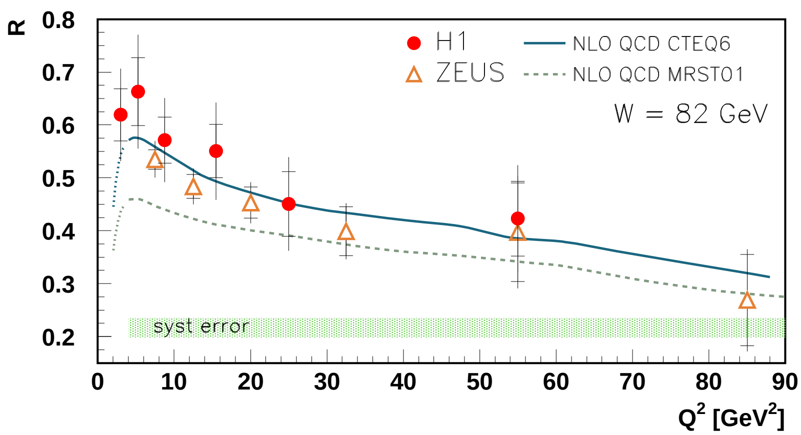

Figure 2: *The skewing factor R as a function of Q^2 at $W = 82$ GeV. The points correspond to the R extraction applied to DVCS measurements of H1 (bullets) and ZEUS (triangles). The curves represent R extracted from Freund et al. prediction based on MRST 2001 and CTEQ6 PDFs.*

for $Q^2 \simeq 2$ GeV^2 down to $R \simeq 0.3$ for $Q^2 \simeq 85$ GeV^2. Qualitatively, the data seem to be consistent with a dependence like $R \propto 1/\log Q^2$. An almost flat W dependence is observed within the present precision. This feature can be easily understood by inspecting Eq. (3), since the W dependence of both the DIS and DVCS cross section is power-like having a proportional effective power. Namely, $\sigma_{\rm DIS} \propto W^{2\lambda}$ and $\sigma_{\rm DVCS} \propto W^{4\lambda}$. The mean value $R \simeq 0.5$ is consistent with its early theoretical estimates using the aligned jet model [8] and the colour dipole saturation model [9].

Q^2 [GeV^2]	R using H1 data		
3	0.62	±0.05	±0.07
5.25	0.66	±0.06	±0.09
8.75	0.57	±0.04	±0.07
15.5	0.55	±0.05	±0.08
25	0.45	±0.06	±0.06
55	0.42	±0.07	±0.07

Q^2 [GeV^2]	R using ZEUS data		
7.5	0.53	±0.02	±0.03
12.5	0.48	±0.02	±0.02
20	0.45	±0.03	±0.02
32.5	0.40	±0.05	±0.03
55	0.41	±0.09	±0.05
85	0.28	±0.09	±0.04

Table 1: *The skewing factor R for different Q^2 values at $W = 82$ GeV according to the DVCS cross section measurement of H1 (left table) and ZEUS (right table).*

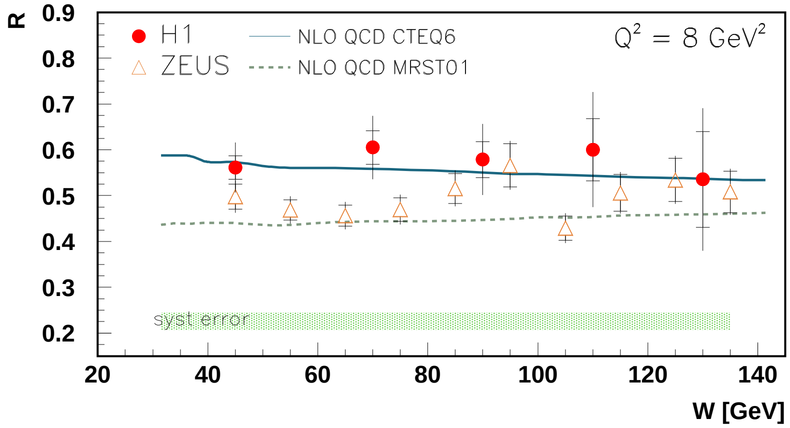

Figure 3: *The skewing factor R as a function of W at $Q^2 = 8$ GeV^2. (see caption of Fig. 2).*

W [GeV]	R using H1 data		
45	0.56	±0.03	±0.05
70	0.60	±0.04	±0.06
90	0.59	±0.04	±0.07
110	0.60	±0.07	±0.10
130	0.53	±0.10	±0.11

W [GeV]	R using ZEUS data		
45	0.50	±0.03	±0.02
55	0.47	±0.02	±0.02
65	0.46	±0.02	±0.02
75	0.47	±0.03	±0.02
85	0.52	±0.03	±0.02
95	0.57	±0.05	±0.03
105	0.43	±0.03	±0.02
115	0.51	±0.04	±0.02
125	0.53	±0.05	±0.02
135	0.51	±0.04	±0.02

Table 2: *The skewing factor R for different W values at $Q^2 = 8$ GeV^2 according to the DVCS cross section measurement of H1 (left table) and ZEUS (right table).*

2 Theoretical Predictions

In this section we compare the results extracted from experimental data to different theoretical predictions. First, we contrast them with the perturbative QCD approach at NLO accuracy. This prediction is dependent on the Generalised Parton Distributions (GPD), which have been parameterised in Ref. [7] and applied to describe the recent DVCS data [5, 6]. The second theoretical approach [9, 11] is given by the colour dipole approach, where the basic building blocks are the photon wavefunctions and the dipole cross section. The non-forward kinematics is encoded by the wavefunctions whereas the off-diagonal effects can be built-in in the parameterisations for the dipole-target cross section.

2.1 NLO QCD Predictions

The DVCS cross section has been calculated at NLO in perturbative QCD by Freund and McDermott [5, 6] using two different GPD parameterisations [7]. The MRST2001 and CTEQ6 parameterisations of the PDFs are used in the DGLAP region and polynomial form is used in the ERBL region, ensuring a smooth continuation between the two regions. Both the skewing (ξ) and the Q^2 dependence are generated dynamically. The t dependence is factorised out and assumed to be $e^{-b|t|}$. In its original form, the approach above used a Q^2-dependent b slope. We have verified that the recent data on DVCS [1] can be reasonably described using a fixed b slope.

Applying the same method presented here (i.e. using the same F_2^p) for the inclusive cross section, the values obtained are shown as a function of Q^2 in Fig. 2 and as a function of W in Fig. 3. The value of $b = 6.02 \pm 0.35 \pm 0.39$ GeV^{-2} measured by H1 [1] has been used in all predictions. The error on the b value is not applied to theoretical predictions as it is already included in the total error of the data points. A good agreement between these predictions and the data points is found, describing well the absolute value of R and its kinematic dependences. The NLO calculation presents no W dependence. The result normalisation is strongly dependent on the choice for the gluon distribution and the deviations seem to be amplified at lower

Q^2. Concerning the behavior on Q^2, it seems that for Q^2 values below $\simeq 4$ GeV^2 the DGLAP evolution starting at $Q_0^2 = 1$ GeV^2 has too little phase space to fully generate the gluon distributions (dotted part of the curves in Fig. 2). The underestimation of R for virtualities below 4 GeV^2 may be due to a larger value for the DVCS cross section calculated at NLO where the gluon distribution is underestimated as an effect of the too small phase space for evolution.

2.2 Colour Dipole Model Predictions

In the colour dipole approach, the DIS (or DVCS) process can be seen as a succession in time of three factorisable subprocesses: i) the virtual photon fluctuates in a quark-antiquark pair, ii) this colour dipole interacts with the proton target, iii) the quark pair annihilates into a virtual (or real) photon. The imaginary part of the DIS (or DVCS) amplitude at $t = 0$ is expressed in the simple way [9],

$$\mathcal{I}m\, \mathcal{A}\,(W, Q_1, Q_2) = \sum_{T,L} \int_0^1 dz \int_0^\infty d^2\boldsymbol{r}\; \Psi^*_{T,L}(z,\, \boldsymbol{r},\, Q_1^2)\, \sigma_{dip}\,(\tilde{x}, \boldsymbol{r}) \Psi_{T,L}(z,\, \boldsymbol{r},\, Q_2^2)\,, \quad (4)$$

where $\Psi(z, \boldsymbol{r}, Q_{1,2})$ are the light cone photon wave functions for transverse and longitudinal photons. The quantity Q_1 is the virtuality of the incoming photon, whereas Q_2 is the virtuality of the outgoing photon. In the DIS case, one has $Q_1^2 = Q_2^2 = Q^2$ and for DVCS, $Q_1^2 = Q^2$ and $Q_2^2 = 0$. The relative transverse quark pair (dipole) separation is labeled by $\boldsymbol{r}$ whilst z (respec. $1 - z$) labels the quark (antiquark) longitudinal momentum fraction.

It should be noticed that the non-forward kinematics for DVCS is encoded in the colour dipole approach through the different weight coming from the photon wavefunctions in Eq. (4). The off-diagonal effects, which affect the gluon and quark distributions in the pQCD approaches, should be included in the parameterisation of the dipole cross section. At the present stage of the development of the colour dipole formalism, we have no accurate theoretical arguments on how to compute skewedness effects from first principles. A consistent approach would be to compute the scattering amplitude in the non-forward case, since the non-forward photon wave function has been recently obtained in Ref. [13]. In this case, the dipole cross section, $\sigma_{dip}\,(x_1, x_2, \boldsymbol{r}, \vec{\Delta})$, depends on the light cone momenta x_1 and x_2 carried by the exchanged gluons, respectively, and on the total transverse momentum transfer $\vec{\Delta}$. In this case, additional information about the dependence upon $\vec{\Delta}$ is needed for the QCD Pomeron and proton impact factor. The forward dipole cross section is recovered at $x_1 = x_2$ and $\vec{\Delta} = 0$.

In Ref. [11] an estimate of the skewedness for the dipole cross section has been performed using the approximation of Ref. [14] where the ratios of off-diagonal to diagonal parton distributions are computed. The behavior of those ratios are given explicitly by:

$$R_{q,\,g}\,(Q^2) = \frac{2^{2\lambda+3}}{\sqrt{\pi}}\,\frac{\Gamma\,\left(\lambda + \frac{5}{2}\right)}{\Gamma\,(\lambda + 3 + p)}\,, \tag{5}$$

where $p = 0$ for quarks and $p = 1$ for gluons, whereas λ is the effective exponent of the parton distribution. The ratio is larger for singlet quarks than for gluons. In the colour dipole picture, the DVCS cross section is driven mainly by gluonic exchanges. In our numerical computations, we use $\lambda = \lambda(Q^2)$ as obtained from the DVCS scattering amplitude and the skewedness effect is given by multiplying the original (without skewedness) total cross section by the factor $R_g^2(Q^2)$. A different implementation of the skewedness correction is to use the approximation $\tilde{x} = 0.41\,x_{\mathrm{Bj}}$, which produces the same effects as for R_g at the presently covered kinematic range and precision of the measurement. This different procedure is particularly suitable for dipole cross sections which are parameterised by using a gluon distribution, namely $\sigma_{dip} \propto \boldsymbol{r}^2 xg\,(x, c/\boldsymbol{r}^2)$.

Using this colour dipole prediction (with DGLAP evolution and off-diagonal skewing factor R_g), one can again extract the R factor, as shown as a function of Q^2 in Fig. 4 and as a function of W in Fig. 5. A good agreement with points extracted from the data is found. The curve obtained without applying the off-diagonal skewing factor R_g is also presented, enabling one to isolate the two effects: the non-forward kinematic and the off-diagonal gluon distributions. En passant these results demonstrate that the approximation of Eq. 5 is reliable within the present precision. Furthermore, the off-diagonal effects contribute mostly for the overall normalisation of the skewing factor whereas the behavior on Q^2 seems to be driven by the non-forward kinematic

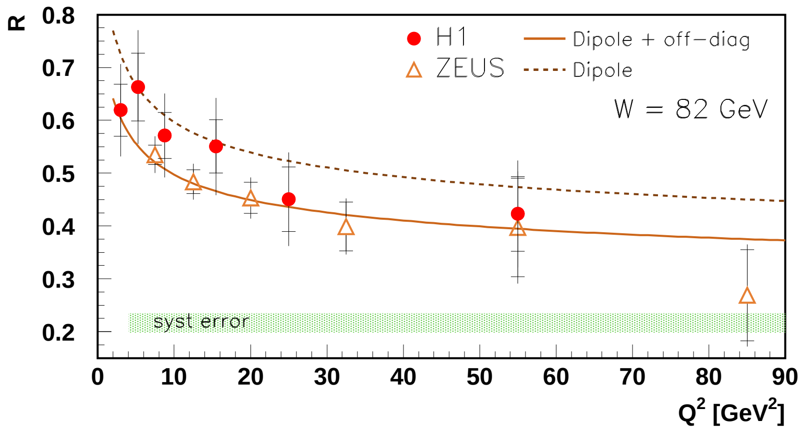

Figure 4: *The skewing factor R as a function of Q^2 at $W = 82$ GeV. The curves represent the theoretical predictions of the colour dipole approach (see text) with (solid) and without (dashed) applying the off-diagonal skewing factor R_g.*

effect. This prediction exhibits a moderate increasing of R with W which is not present in the NLO prediction.

Let us perform a qualitative analysis in order to obtain a physical picture for the W and Q^2 dependences of the skewing factor. We take the colour dipole approach and the saturation model for the dipole cross section [10], considering for simplicity the massless case. The final result should be sufficiently independent of this particular choice for the dipole cross section. One can use an approximated form for the dipole cross section from the saturation model; $\sigma_{dip} = \sigma_0 \, r^2 \, Q_s^2(x)/4$ (colour transparency) for $r^2 \leq 4/Q_s^2(x)$ and $\sigma_{dip} = \sigma_0$ (black disk limit) for $r^2 > 4/Q_s^2(x)$. The saturation scale is given by $Q_s^2(x) \propto \Lambda^2_{\mathrm{QCD}} \, x^{-\lambda}$ and gives the onset of nonlinear corrections to the QCD dynamics. As the DVCS data are predominantly at intermediate Q^2, we will be interested in small size colour dipoles (here, the dipole cross section is dominated by colour transparency behavior). In this particular region, we found in Ref. [9] the qualitative behavior for the total DVCS cross section, taking into account only the non-forward kinematic effect,

$$\sigma(\gamma^* \, p \to \gamma \, p) \propto \frac{Q_s^4}{Q^4} \, \left[1 + \log \left(\frac{Q^2}{Q_s^2(x)} \right) \right]^2 , \tag{6}$$

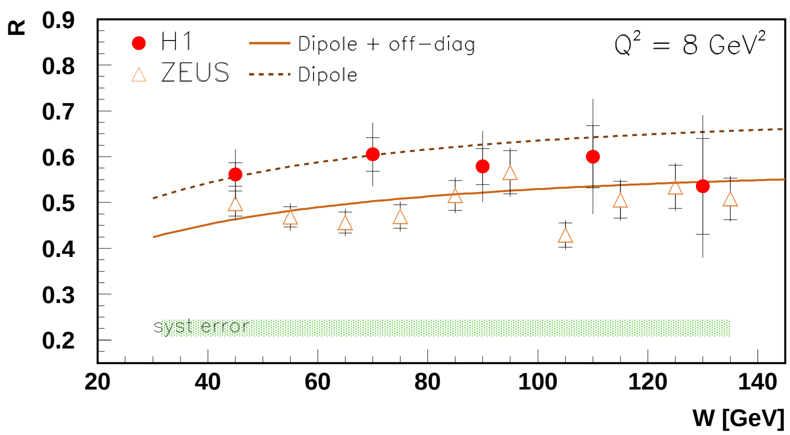

Figure 5: *The skewing factor R as a function of W at $Q^2 = 8$ GeV^2. (see caption of Fig. 4).*

where the large logarithm in Eq. (6) originates from the intermediate region $2/Q < r < 2/Q_s(x)$ and the remaining comes from the region $2/Q_s(x) < r < 2/Q$ in the dipole size integration in Eq. (4).

The qualitative result above can be contrasted with the DIS case, where the $\gamma^* p$ total cross section grows as $\sim W^{2\lambda}/Q^2$ at intermediate Q^2. In particular, DIS data are proven to exhibit a geometric scaling pattern in the scaling variable $\tau = Q^2/Q_s^2$. It is also easy to demonstrate that DVCS data also should present such a scaling behavior. In particular, at intermediate Q^2 it is shown that the experimental DIS cross section behaves as $\sigma(\gamma^* p \to X) \simeq 1/\tau = Q_s^2/Q^2$. Putting this information together and the result for the DVCS cross section presented in Eq. (6) into the definition of the skewing factor, Eq. (3), one obtains,

$$R\,(W, Q^2) \propto \left[1 + \log\left(\frac{Q^2}{Q_s^2(x)}\right)\right]^{-1}\,, \qquad (7)$$

where in the DESY-HERA domain the saturation scale takes values of $Q_s^2 = 1-2$ GeV^2. Therefore, the qualitative Q^2 behavior for the skewing factor takes the form $R \propto 1/(1+\log Q^2)$. On the other hand, one has $Q_s^2 \simeq x^{-\lambda} \approx (W/Q)^{2\lambda}$ which at fixed virtualities the skewing factor behaves as $R \propto 1/(1-\varepsilon \log W)$. These qualitative results are in agreement with the behavior of the experimental extraction of R. One notice that the early theoretical determinations for R predict $R \simeq \log^{-1}[1 + (Q^2/M_0^2)]$, with $M_0^2 \simeq 0.4$-0.6 GeV^2, in close proximity with the present estimate [8].

3 Summary

The skewing factor R, defined as the ration of the imaginary parts of the DIS and DVCS amplitudes has been extracted from experimental data for the first time. In its determination one uses the recent Deeply Virtual Compton Scattering (DVCS) and the inclusive inelastic cross section measurements at DESY-HERA. The main theoretical uncertainties come from the b slope and from the estimate for the real part contribution. One founds a Q^2 dependence qualitatively consistent with the form $R \propto 1/\log Q^2$. No W dependence is observed within the current precision. The mean value $R \simeq 0.5$ is consistent with previous theoretical estimates in the jet aligned model and colour dipole picture. The extracted R is contrasted to theoretical predictions of NLO QCD and colour dipole approaches. The first one uses two different GPD parameterisations and produces a consistent description for the W and Q^2 dependences of the skewing factor. The colour dipole formalism, supplemented by a dipole cross section including QCD evolution and off-diagonal corrections successfully describes R. In particular, a qualitative understanding of the dependences of R is obtained relying on simple arguments in the dipole formalism. This study confirms a behavior of the form $R \propto 1/(1 + \log Q^2)$ and flat dependence upon W. Beyond the successfully described dependences in Q^2 and W achieved here, to perform a further discussion on the normalisation of R, a better agreement within experimental DVCS cross section measurements has to be achieved.

Acknowledgments

The authors thank the support of the High Energy Physics Group at Institute of Physics of Porto Alegre. The work of L. Favart is supported by the FNRS of Belgium (convention IISN 4.4502.01).

References

[1] C. Aktas *et al.* [H1 Collaboration], Eur. Phys. J. C **44**, 1-11 (2005), [hep-ex/0505061].

[2] S. Chekanov *et al.* [ZEUS Collaboration], Phys. Lett. B **573**, 46 (2003), [hep-ex/0305028].

[3] C. Adloff *et al.* [H1 Collaboration], Phys. Lett. B 520, 183 (2001), [hep-ex/0108035].

[4] C. Adloff *et al.* [H1 Collaboration], Eur. Phys. J. C21 (2001) 33-61, [hep-ex/0012053].

[5] A. Freund and M.F. McDermott, Phys. Rev. D **65** (2002) 091901, [hep-ph/0106124].

[6] A. Freund and M.F. McDermott, Phys. J. C **23** (2002) 651-674, [hep-ph/0111472].

[7] A. Freund, M.F. McDermott and M. Strikman, Phys. Rev. D **67** (2003) 036001, [hep-ph/0208160].

[8] L. L. Frankfurt, A. Freund and M. Strikman, Phys. Rev. D **58**, 114001 (1998) [Erratum-ibid. D **59**, 119901 (1999)], [hep-ph/9710356].

[9] L. Favart and M. V. Machado, Eur. Phys. J. C **29**, 365 (2003), [hep-ph/0302079].

[10] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **60** (1999) 114023, [hep-ph/9903358].

[11] L. Favart and M.V. Machado, Eur. Phys. J. C **34** (2004) 429, [hep-ph/0402018].

[12] J. Bartels, K. Golec-Biernat and H. Kowalski, Acta Phys. Polon. B **33** (2002) 2853, [hep-ph/0207031].

[13] J. Bartels, K. Golec-Biernat and K. Peters, Acta Phys. Polon. B **34**, 3051 (2003), [hep-ph/0301192].

[14] A. G. Shuvaev, K. J. Golec-Biernat, A. D. Martin and M. G. Ryskin, Phys. Rev. D **60**, 014015 (1999), [hep-ph/9902410].