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A deeply virtual Compton scattering amplitude

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Abstract

A factorized Regge-pole model for deeply virtual Compton scattering is suggested. The use of an effective logarithmic Regge-pomeron trajectory provides for the description of both "soft" (small $|t|$) and "hard" (large $|t|$) dynamics. The model contains explicitly the photoproduction and the DIS limits and fits the existing HERA data on deeply virtual Compton scattering.

1. Introduction

Interest in deeply virtual Compton scattering (DVCS) $ep \to e\gamma p$ to large extent is triggered by the prospects to use it as a tool in studies of generalized parton distributions (GPD) [1,2].

At HERA the DVCS cross-section has been measured [3,4], in diffractive ep interactions, as a function of Q^2, W and t that are respectively the photon virtuality, the invariant mass of the $\gamma^* p$ system and the squared 4-momentum transferred at the proton vertex; the diagram in Fig. 1(a) shows the production of a real photon at HERA.

The Q^2 evolution of the DVCS amplitude has been studied in several papers, mainly in the context of perturbative quantum chromodynamics (QCD) [5,6] and recently in [7]. The t dependence in many papers was introduced by a simple factorized exponential in t, which however differs from the Regge pole theory. Since the electron–proton scattering at HERA is dominated by a single photon exchange, the calculation of the DVCS scattering amplitude reduces to that of the $\gamma^* p \to \gamma p$ amplitude, which at high energies, in the Regge pole approach, is dominated by the exchange of positive-signature reggeons, associated with the pomeron- and the f-trajectories [8]. This DVCS amplitude is shown in Fig. 1(b) in a Regge-factorized form. In the figure $q_{1,2}$ are the four-momenta of the incoming and outgoing photons, $p_{1,2}$ are the four-momenta of the incoming and outgoing protons, r is the four-momentum of the reggeon exchanged in the t channel, $r^2 = t = (q_1 - q_2)^2$ and $s = W^2 = (q_1 + p_1)^2$ is the squared centre-of-mass energy of the incoming system.

Unless specified (as in the deep inelastic scattering (DIS) limit, discussed in Section 3), $q_2^2 = 0$, and hence, for brevity, $q_1^2 = -Q^2$. In the upper vertex V_1, Fig. 1(b), a virtual photon with 4-momentum q_1, and a reggeon (e.g. pomeron) with 4-momentum r, enter and a real photon, with 4-momentum $q_2 = q_1 + r$ appears in the final state as an outgoing particle. The vertex V_1 depends on all the possible invariants constructed with the above 4-momenta, $V_1[q_1^2, r^2, q_1 \cdot r]$, where $r^2 = t \leqslant 0$, $q_1^2 = -Q^2 \leqslant 0$. The three invariants are not independent since the mass-shell condition for the outgoing photon, $q_2^2 = (q_1 + r)^2 = 0$, provides the relation

$$q_1 \cdot r = \frac{-q_1^2 - r^2}{2} = \frac{Q^2 - t}{2}. \tag{1}$$

Hence, the vertex can be considered as a function of the invariants $[Q^2, q_1 \cdot r]$ or $[t, q_1 \cdot r]$. This does not mean that the variables cannot appear separately but it could also happen that $q_1 \cdot r$ becomes a scaling variable, and consequently the vertex

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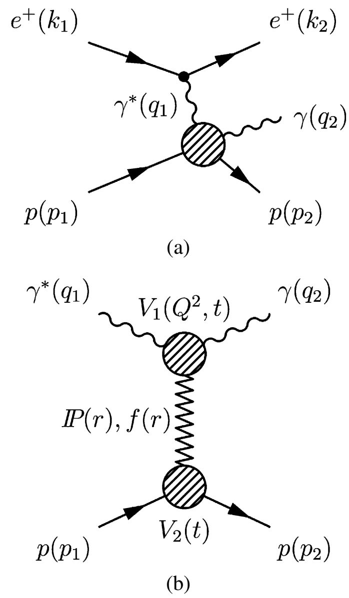

Fig. 1. (a) Diagram of a DVCS event at HERA; (b) DVCS amplitude in a Regge-factorized form.

will finally depend on $q_1 \cdot r$ only. It depends on the dynamics of the process and, for the moment, we prefer to keep t, apart from Q^2, as the second independent variable.

Electroproduction of a vector meson gives another example since in this case $(q_1+r)^2 = M_V^2$, and the variable $q_1 \cdot r$ becomes

$$q_1 \cdot r = \frac{M_V^2 - q_1^2 - r^2}{2} = \frac{M_V^2 + Q^2 - t}{2}. \tag{2}$$

The interplay of the Q^2- and t-dependence in the DVCS amplitude was recently discussed in Ref. [9], where the existence of a new, universal variable z was suggested. The basic idea is that Q^2 and t, both having the meaning of the squared mass of a virtual particle (photon or reggeon), should be treated by means of the variable, defined as

$$z = q_1^2 + t = -Q^2 + t, \tag{3}$$

in the same way as the vector meson mass squared is added to the squared photon virtuality, giving $\tilde{Q}^2 = Q^2 + M_V^2$ in the case of vector meson electroproduction [10,11].

In this Letter we examine an explicit model for DVCS with Q^2- and t-dependences determined by the $\gamma^*\mathbb{P}\gamma$ vertex. We suggest the use of the new variable defined in Eq. (3) with its possible generalization to vector meson electroproduction,

$$z = t - \left(Q^2 + M_V^2\right) = t - \tilde{Q}^2 \tag{4}$$

or virtual photon (lepton pair) electroproduction,

$$z = t - \left(Q_1^2 + Q_2^2\right), \tag{5}$$

where $Q_2^2 = -q_2^2$. However, differently from Ref. [9], here we introduce the new variable only in the upper, $\gamma^*\mathbb{P}\gamma$ vertex, to which the photons couple.

In the next section we introduce the model. Its viability is supported by the correct photoproduction- ($Q^2 = 0$) and DIS- ($Q^2 > 0$ and $t \to 0$) limits, demonstrated in Section 3. Fits to the data are presented in Section 4, while discussions and conclusions are in Section 5.

2. The model

According to Fig. 1(b), this DVCS amplitude can be written as

$$A\left(s,t,Q^2\right)_{\gamma^* p \to \gamma p} = -A_0 V_1\left(t,Q^2\right) V_2(t) (-is/s_0)^{\alpha(t)}, \tag{6}$$

where A_0 is a normalization factor, $V_1(t,Q^2)$ is the $\gamma^*\mathbb{P}\gamma$ vertex, $V_2(t)$ is the $p\mathbb{P}p$ vertex and $\alpha(t)$ is the exchanged pomeron trajectory, which we assume in a logarithmic form:

$$\alpha(t) = \alpha(0) - \alpha_1 \ln(1 - \alpha_2 t). \tag{7}$$

Similar to [7], we consider only the helicity conserving amplitude.

Trajectory (6) is nearly linear for small $|t|$, thus reproducing the forward cone of the differential cross-section, while its logarithmic asymptotics provides for the large-angle scaling behavior [12,13], typical of hard collisions at small distances, with power-law fall-off in $|t|$, obeying quark counting rules [12,14,15]. Here we are referring to the dominant pomeron contribution plus a secondary trajectory, e.g. the f-reggeon. Although we are aware of the importance of this subleading contribution at HERA energies, nevertheless we cannot afford the duplication of the number of free parameters, therefore we include it effectively by rescaling the parameters. Ultimately, the pomeron and the f-reggeon have the same functional form, differing only in the values of their parameters. Furthermore, the pomeron [16] itself is unlikely to be a single term, so instead of including several Regge terms with many free parameters, it may be reasonable to comprise them in a single term, called “effective reggeon” or “effective pomeron”, depending on the kinematical region of interest. Although the parameters of this effective reggeon (pomeron) (e.g. its intercept and slope) can be close to the “true” one (whose form is at best a convention), for the above reason they never should be taken for granted.

For convenience, and following the arguments based on duality (see Ref. [17] and references therein), the t dependence of the $p\mathbb{P}p$ vertex is introduced via the $\alpha(t)$ trajectory: $V_2(t) = e^{b\alpha(t)}$ where b is a parameter. A generalization of this concept will be applied also to the upper, $\gamma^*\mathbb{P}\gamma$ vertex by introducing the “trajectory”

$$\beta(z) = \alpha(0) - \alpha_1 \ln(1 - \alpha_2 z), \tag{8}$$

where the value of the parameter α_2 may be different in $\alpha(t)$ and $\beta(z)$ (a relevant check will be possible when more data will be available). Hence the scattering amplitude (6), with the correct signature, becomes

$$\begin{aligned} A\left(s,t,Q^2\right)_{\gamma^* p \to \gamma p} &= -A_0 e^{b\alpha(t)} e^{b\beta(z)} (-is/s_0)^{\alpha(t)} \\ &= -A_0 e^{(b+L)\alpha(t) + b\beta(z)}, \end{aligned} \tag{9}$$

where $L \equiv \ln(-is/s_0)$.

The model contains a limited number of free parameters. Moreover, most of them can be estimated a priori. The product

$\alpha_1\alpha_2$ is just the forward slope α' of the reggeon (≈ 0.2 GeV^{-2} for the pomeron, but much higher for f and/or for an effective reggeon).[1] The value of α_1 can be estimated from the large-angle quark counting rules [12,14,15]. In a dual model, the value of α_1 can be estimated from the large-angle quark counting rules since, for large t ($|t| \gg 1$ GeV^2), the amplitude goes roughly like $\sim e^{-\alpha_1 \ln(-t)} = (-t)^{-\alpha_1}$ (for more details see Ref. [12]). In this case the power α_1 is related to the number of quarks in a collision. The amplitude (9), however, does not scale exactly since it contains an extra s-dependent factor, for which reason the above arguments are only approximate. We made trials with α_1 ranging from 1 to 4 and found little variation of the resulting fits, moreover the best χ^2 was achieved with α_1 close to 1. Following this indication, we fixed α_1 at 1, thus reducing the number of the free parameters by one.

We fixed the intercept of our effective reggeon, dominated by the pomeron, at $\alpha(0) = 1.25$, as an "average" over the "soft + hard" pomerons.[2] Finally, following dual models, we set the otherwise unknown Regge scaling parameter $s_0 = 1/\alpha'$.

The above values of the parameters should not be taken for granted, rather they should be considered as starting values in the fitting procedure presented in Section 4.

From Eq. (9) the slope of the forward cone is

$$B(s, Q^2, t) = \frac{d}{dt} \ln |A|^2 = 2\left[b + \ln\left(\frac{s}{s_0}\right)\right]\frac{\alpha'}{1-\alpha_2 t} + 2b\frac{\alpha'}{1-\alpha_2 z}, \tag{10}$$

which, in the forward limit, $t = 0$ reduces to

$$B(s, Q^2) = 2\left[b + \ln\left(\frac{s}{s_0}\right)\right]\alpha' + 2b\frac{\alpha'}{1+\alpha_2 Q^2}. \tag{11}$$

Thus, the slope shows shrinkage in s and antishrinkage in Q^2.

3. Photoproduction- and DIS-limits

In the $Q^2 \to 0$ limit Eq. (9) becomes

$$A(s, t) = -A_0 e^{2b\alpha(t)} (-is/s_0)^{\alpha(t)}, \tag{12}$$

where we recognize a typical Regge-behaved photoproduction (or, for $Q^2 \to m_H^2$, on-shell hadronic (H)) amplitude. The related deep inelastic scattering structure function is recovered by setting $Q_2^2 = Q_1^2 = Q^2$ and $t = 0$, to get a typical elastic virtual forward Compton scattering amplitude:

$$A(s, Q^2) = -A_0 e^{b(\alpha(0) - \alpha_1 \ln(1+\alpha_2 Q^2))} e^{(b + \ln(-is/s_0))\alpha(0)} \propto -(1+\alpha_2 Q^2)^{-\alpha_1} (-is/s_0)^{\alpha(0)}. \tag{13}$$

For not too large Q^2 the contribution from longitudinal photons is small (it vanishes for $Q^2 = 0$). Moreover, at high energies, typical of the HERA collider, the amplitude is dominated by the helicity conserving pomeron exchange and, since the final photon is real and transverse, the initial one is also transverse—to the extent that helicity is conserved. Hence the relevant structure function is F_1 that, at leading order, is related to F_2 by the Callan–Gross relation, to be used in obtaining Eq. (14).

For $t = 0$ (with $x \approx Q^2/s$, valid for large s), the structure function assumes the form:

$$F_2(s, Q^2) \approx \frac{(1-x)Q^2}{\pi\alpha_e} \Im A(s, Q^2)/s, \tag{14}$$

where α_e is the electromagnetic coupling constant and the normalization is $\sigma_t(s) = \frac{4\pi}{s}\Im A(s, Q^2)$. It has the correct (required by gauge invariance) $Q^2 \to 0$ limit and has Bjorken scaling behavior for large enough s and Q^2. Its behavior, compared with relevant DIS data, will illustrated in the next section, in Fig. 3.

The model fails at large Q^2, where Bjorken scaling is known to be badly violated, and Regge behavior should be replaced by (or appended with) the DGLAP evolution, as shown, for example, in Ref. [19]. An explicit model interpolating between Regge behavior at small and intermediate Q^2 and the approximate solution of the DGLAP equation at large Q^2 was developed in Ref. [20]. In any case, a "global fit" to DVCS and DIS data would require also the inclusion of both the longitudinal and transverse photons.

4. Fits to the $ep \to e\gamma p$ data; DIS

A standard procedure for the fit to the HERA data on DVCS [3,4] based on Eq. (9) has been adopted. A detailed analysis of the data would require a sum of a pomeron plus an f-reggeon contribution:

$$A = A^P + A^f. \tag{15}$$

To avoid the introduction of too many parameters, given the limited number of experimental data points, we use a single reggeon term, as already discussed in Section 2, which can be treated as an effective reggeon. The parameters $\alpha(0)$, α_1 and α' have been fixed to 1.25, 1.0 and 0.38 GeV^{-2} respectively and the values of the fitted parameters A_0 and b, described in Eq. (9) are listed in Table 1. The value of α' has been determined in an exploratory fit with this parameter left free to vary between 0.2 and 0.4 GeV^{-2}.

Table 1
The values of the fitted parameters quoted in Eq. (9)

Parameter	σ_{DVCS} vs. Q^2	σ_{DVCS} vs. t	σ_{DVCS} vs. W
$\|A_0\|^2$	0.08 ± 0.01	0.11 ± 0.24	0.06 ± 0.01
b	0.93 ± 0.05	1.04 ± 0.91	1.08 ± 0.10
χ^2/ndof	0.57	0.15	1.15

[1] As emphasized in a number of papers, e.g. in Ref. [18], the wide-spread prejudice of the "flatness" of the pomeron in electroproduction is wrong for at least two reasons: one is that it was deduced by fitting data to a particular "effective reggeon" (see the relevant discussion above) and the second is that the pomeron is universal, and its nonzero slope is well known from hadronic reactions.

[2] This is an obvious simplification and we are fully aware of the variety of alternatives for the energy dependences, e.g. that of a dipole pomeron, as in Ref. [17], a "soft" plus a "hard" one, as e.g. in Ref. [5]. Ultimately, from QCDs BFKL equation [16] an infinite number of pomeron singularities follows unless simplifications are used. For the present study in term of the new, z, variable the simplest "supercritical" pomeron [5] with an effective intercept is suitable.

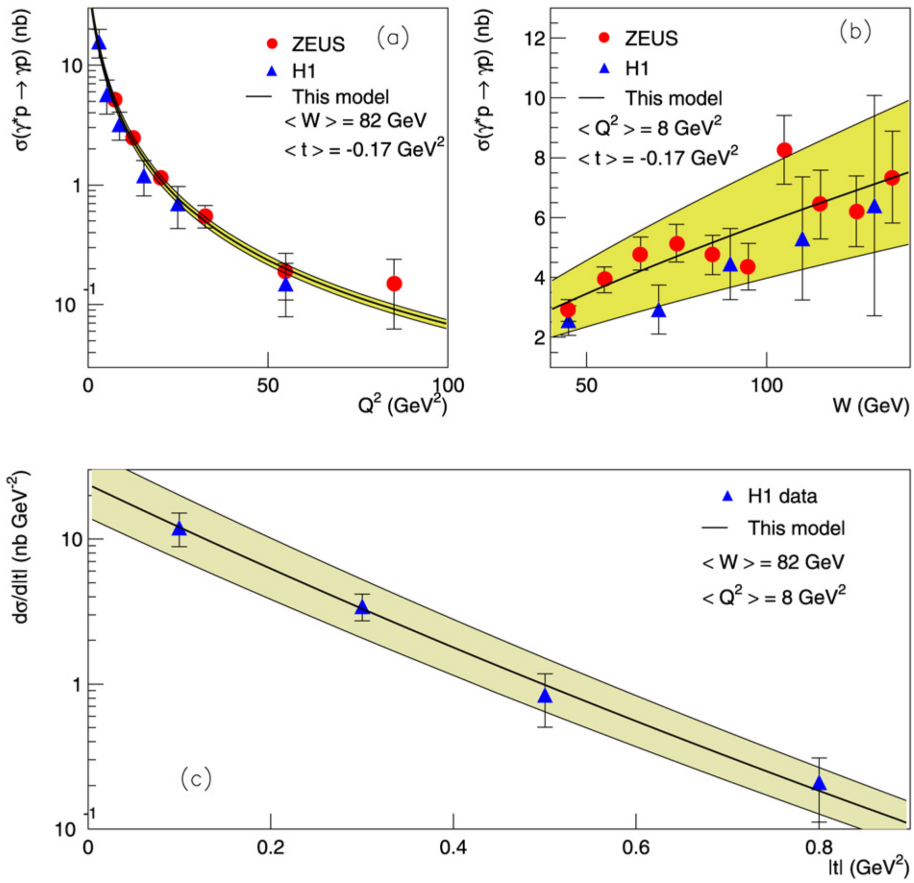

Fig. 2. The $\gamma * p \to \gamma p$ cross-section as a function of Q^2 (a), of W (b) and the cross-section differential in t (c) measured by H1 and ZEUS experiments [3,4]. The ZEUS measurements have been rescaled to the W and Q^2 H1 values. The lines show the results of the fits obtained from Eq. (16) to the data.

The ZEUS measurements have been rescaled to the W and Q^2 values of the H1 measurements. The mean value of $|t|$ has been fixed to 0.17 GeV^2 according with the H1 measurements of the differential cross-section in the range (0.1–0.8) GeV^2 for H1 [3] taking into account the value 6.02 GeV^{-2} for the slope B as determined by the experiment. In the fit of the DVCS cross section as a function of W the parameters $|A_0|^2$ and b have been constrained in the range (0–0.2) and (0–1.2), respectively.

The results of the fits to the HERA data on DVCS are shown in Fig. 2. The cross-section $\sigma(\gamma^* p \to \gamma p)$ as a function of Q^2 and $W = \sqrt{s}$ are presented respectively in Fig. 2(a) and (b). The differential cross-section $d\sigma(\gamma^* p \to \gamma p)/dt$, given by

$$\frac{d\sigma}{dt}\left(s,t,Q^2\right) = \frac{\pi}{s^2}\left|A\left(s,t,Q^2\right)\right|^2, \tag{16}$$

is presented in Fig. 2(c).

The quality of the fits is satisfactory; in particular our model fits rather well the cross-sections as a function of Q^2 and the cross-section differential in t. Although the present HERA data on DVCS are well within the "soft" region, the model potentially is applicable for much higher values of $|t|$, dominate by hard scattering.

The behavior of $F_2(s, Q^2)$ at small x and moderate Q^2 with the parameters fitted above to the DVCS data, is shown in Fig. 3.

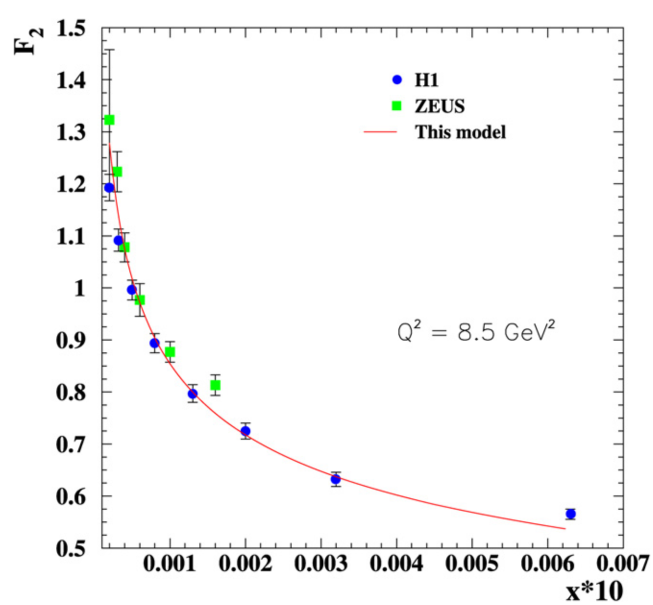

Fig. 3. The behavior of the DIS structure function, Eq. (14) shown together with the H1 [21] and ZEUS [22] data.

Finally, Fig. 4 shows antishrinkage in Q^2 and shrinkage in W of the forward cone, according to Eqs. (10) and (11). The curves are compared with the H1 experimental results.

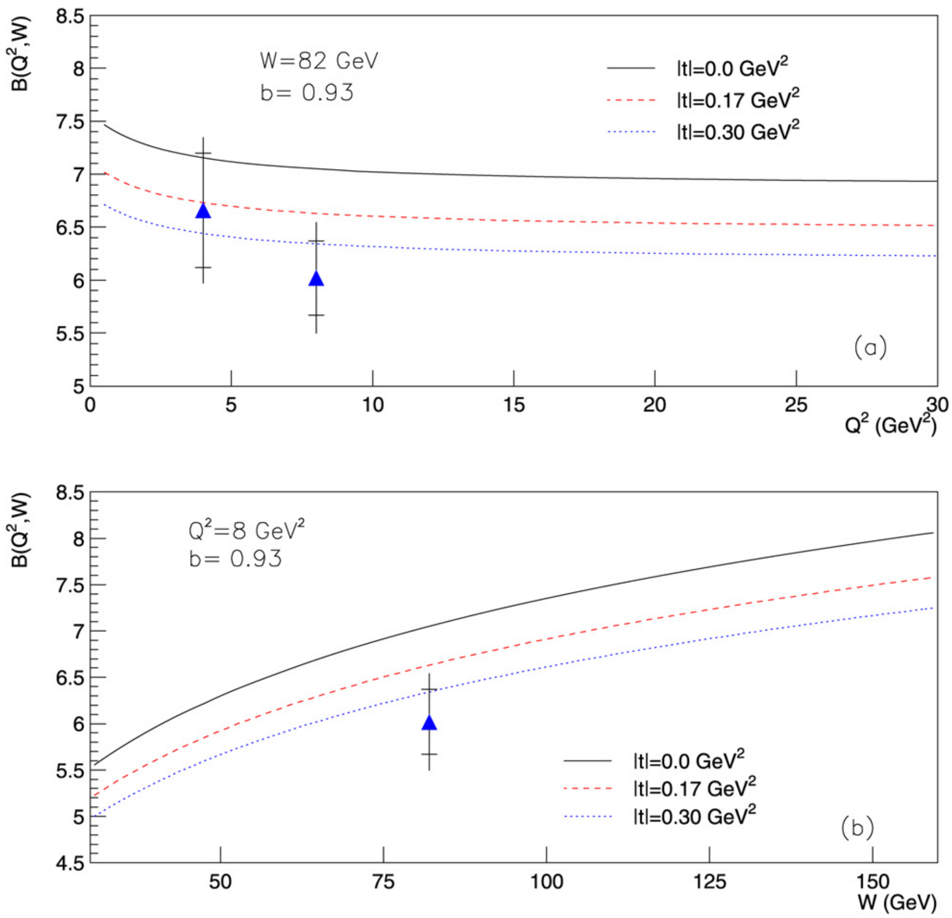

Fig. 4. The Q^2- and W-dependence of the local slope described in Eq. (10) (dotted and dashed line) and Eq. (11) (solid line). The triangles show the experimental measurements of H1.

5. Conclusions and discussion

The model presented in this Letter may have two-fold applications. On one hand, it can be used by experimentalists as a guide. The fits to the data could be improved, when more data are available, by accounting for the pomeron and f-reggeon contributions separately as well as by using expressions for Regge trajectories which take into account analyticity and unitarity. On the other hand, the model can be used to study various extreme regimes of the scattering amplitude in all the three variables it depends on. For that purpose, however, the transition from Regge behavior to QCD evolution at large Q^2 should be accounted for. A formula interpolating between the two regimes (Regge pole and asymptotic QCD evolution) was proposed in Ref. [20] for $t = 0$ only. Its generalization to nonzero t values is possible by applying the ideas and the model presented in this Letter. The applicability of the model in both soft and hard domains can be used to learn about the transition between perturbative (QCD) and nonperturbative (Regge poles) dynamics.

Independently of the pragmatic use of this model as a instrument to guide experimentalists, given its explicit form, it can be regarded also as an explicit realization of the corresponding principle [23] of exclusive–inclusive connection in various kinematical limits.

Last but not least, the simple and feasible model of DVCS presented in this Letter can be used to study general parton distributions (GPD). As emphasized in Ref. [24], in the first approximation, the imaginary part of the DVCS amplitude is equal to a GPD. The presence of the Regge phase in our model can be used for restoring the correct phase of the amplitude, for which the interference experiments (with Bethe–Heitler radiation) are designed.

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