DIS, DEEPLY VIRTUAL COMPTON SCATTERING AND VECTOR MESON PRODUCTION* **

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The QCD-based generalized vector dominance-color-dipole picture (GVD-CDP) provides a coherent picture of low-x DIS, deeply virtual Compton scattering and light as well as heavy vector–meson production.

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More than thirty years ago, it was suggested [1, 2] that deeply inelastic scattering of electrons from nucleons at low $x \cong Q^2/W^2$ was to be understood in terms of the forward-scattering amplitude of a continuum of massive hadronic vector states the photon was supposed to virtually dissociate into, or, in modern jargon, "to fluctuate into". A mass dispersion relation was set up to quantitatively formulate this picture of generalized vector dominance (GVD). Concerning the energy dependence of the virtual photoabsorption cross section, $\sigma_{\gamma^* p}(W^2, Q^2)$, not surprisingly, the simplest assumption was adopted, an energy dependence determined by what nowadays is called the "soft" Pomeron.

When HERA came into operation about ten years ago, an appreciable fraction of the hadronic events ("large-rapidity gap events") was found to show typical features of diffractive production, whereby including the production of a massive continuum of hadronic states as well as the elastic production of the vector mesons, $\rho^0, \omega, \phi, J/\psi$ and Υ. The energy dependence found in diffractive production and for the total photoabsorption cross section, however, for sufficiently large Q^2, turned out to be much stronger than expectations based on the soft Pomeron relevant for (real) photoproduction and hadron–hadron-scattering.

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The experimental data on $\sigma_{\gamma^* p}(W^2, Q^2)$ for $x \ll 1$, in good approximation, in a model-independent analysis were found [3] to lie on a single curve when plotted against the variable [3]

$$\eta = \frac{Q^2 + m_0^2}{\Lambda^2(W^2)}\,, \tag{1}$$

where [4]

$$\begin{aligned} m_0^2 &= 0.15 \pm 0.04\,\mathrm{GeV}^2\,, \\ \Lambda^2(W^2) &= B\left(\frac{W^2}{W_0^2} + 1\right)^{C_2} \end{aligned} \tag{2}$$

with

$$\begin{aligned} B &= 2.24 \pm 0.43\ \mathrm{GeV}^2\,, \\ W_0^2 &= 1081 \pm 124\ \mathrm{GeV}^2\,, \\ C_2 &= 0.27 \pm 0.01\,. \end{aligned} \tag{3}$$

The modern QCD-based analysis of low-x DIS describes the Pomeron as a two-gluon-exchange object [5]. The virtual photon at low x fluctuates into a $(q\bar{q})^{J=1}$ (vector) state, as in GVD, and the $(q\bar{q})^{J=1}$ color dipole, in the virtual Compton-forward-scattering amplitude, interacts with the proton via two-gluon exchange. A detailed analysis reveals that the resulting virtual forward-Compton amplitude embodies a structure of the form of the aforementioned mass-dispersion relation [6,7]. The quark propagators in the quark loop of the two-gluon exchange become transmogrified into propagators of $(q\bar{q})^{J=1}$ vector states of mass

$$M_{q\bar{q}}^2 = \frac{\vec{k}_\perp^2 + m_q^2}{z(1-z)}\,, \tag{4}$$

where $k_\perp$ and m_q refer to transverse three-momentum and mass of the quark (antiquark) and z to the fraction of the light-cone momentum of the photon carried by the quark. Our formulation [3] for the total photoabsorption cross section in terms of the photon-lightcone wave function and the color-dipole cross section explicitly incorporates [8] the spin $J = 1$ nature of the color dipole in the color-dipole forward-scattering amplitude, *i.e.* the dipole-cross section refers to the scattering of $(q\bar{q})^{J=1}$ (vector) states (generalized vector dominance — color dipole picture, GVD-CDP). This allowed us to derive sum rules [8] that express the longitudinal and transverse total photoabsorption cross section as an appropriate integral over the mass of the diffractively produced $(q\bar{q})^{J=1}$ continuum, including the low-lying discrete vector-meson states. A direct test of the sum rules requires the extraction of the $(q\bar{q})^{J=1}$ component in the experimental data for diffractive production that has not been accomplished so far. The underlying structure of the theory may be tested, however, by confronting the parameter-free predictions for vector-meson production with the experimental data, and we will come back to that below.

In the QCD-based GVD-CDP, the total photoabsorption cross section in the limits of $\eta \ll 1$ and $\eta \gg 1$, is given by [3]

$$\sigma_{\gamma^* p}(W^2, Q^2) = \frac{\alpha R_{e^+e^-}}{3\pi} \sigma^{(\infty)} \begin{cases} \ln(1/\eta), & (Q^2 \ll \Lambda^2(W^2)), \\ 1/2\eta, & (Q^2 \gg \Lambda^2(W^2)), \end{cases} \tag{5}$$

and $\Lambda^2(W^2)$ becomes identified with the average or effective value of the gluon transverse (three) momentum absorbed by the quark (antiquark), via [4]

$$\langle \vec{l}_\perp^{\,2} \rangle = \frac{1}{6} \Lambda^2(W^2) \, . \tag{6}$$

An important comment concerns to gluon structure function. For $Q^2 \gg \Lambda(W^2)$ in a dual description, one may alternatively describe $\sigma_{\gamma^* p}(W^2, Q^2)$ in terms of γ^*-gluon scattering, and introduce the concept of a gluon density or gluon structure function. Accordingly, we have the identification [9, 10]

$$\frac{1}{8\pi^2} \sigma^{(\infty)} \Lambda^2(W^2) \equiv \alpha_s(Q^2) x g(x, Q^2), \tag{7}$$

where $W^2 = Q^2/x$. It is frequently argued that the gluon-structure function should eventually stop its growth with decreasing x at fixed Q^2, because of the unitarity restrictions on the total photoabsorption cross section. From our point of view, there is a peaceful coexistence with unitarity of an ever rising "gluon density". Indeed, at any fixed Q^2, for sufficiently large energy (*i.e.* sufficiently small x) the interpretation of $\sigma^{(\infty)} \Lambda^2(W^2)$ as a gluon density simply breaks down, and the logarithmic domain in (5) takes over, and finally, at any fixed Q^2, we reach the (non-perturbative) saturation limit of photoproduction [4]

$$\lim_{\substack{W^2 \to \infty \\ Q^2 \text{ fixed}}} \frac{\sigma_{\gamma^* p}(W^2, Q^2)}{\sigma_{\gamma p}(W^2)} = 1 \, . \tag{8}$$

As mentioned, a direct test of the QCD-based GVD-CDP is provided by comparing its parameter-free predictions for $(q\bar{q})^{J=1}$ vector-state forward production with experiment. So far, data are only available for the production of vector mesons, since an extraction of the $J = 1$ part in the diffractive

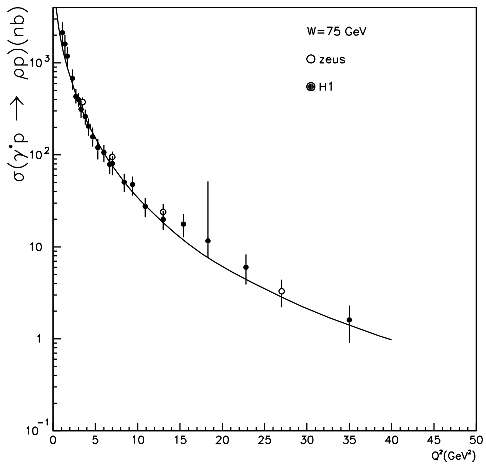

Fig. 1. The Q^2 dependence of ρ^0 production, $\gamma^* p \to \rho^0 p$, at fixed $W = 75$ GeV, compared with the predictions from the QCD-based GVD-CDP.

continuum has not been carried out. As an example, in Fig. 1, we show the GVD-CDP predictions [11] compared with the data for ρ^0 production, whereby a constant slope of $b = 7.5\,\mathrm{GeV}^{-2}$ was inserted. The prediction in Fig. 1 is obtained by applying quark-hadron duality to the diffractively produced $(q\bar{q})^{J=1}$ continuum in the ρ^0-mass region. While for ρ^0 production the approximation by massless quarks is relevant, *i.e.* $M^2_{\rho^0} \gg 4m_q^2 \cong 0$, in the case of J/ψ and Υ, the approximation $M_V^2 \cong 4m_q^2$ must be used. From the light-cone wave functions, at threshold, for $z(1-z) = \frac{1}{4}$, one finds the substitution prescription [11]

$$Q^2 \to Q^2 + 4m_q^2 \tag{9}$$

to pass from the massless-quark case to the massive-quark case. Again applying quark–hadron duality, one finds an enhancement, [11]

$$E^{(V)} \equiv \frac{R^{(\rho^0)}}{R^{(V)}} \frac{\sigma_{\gamma^* p \to V p}}{\sigma_{\gamma^* p \to \rho^0 p}}\,, \qquad \left(\frac{R^{(\rho^0)}}{R^{(J/\psi)}} = \frac{9}{8}\,,\ \frac{R^{(\rho^0)}}{R^{(\Upsilon)}} = \frac{9}{2} \right), \tag{10}$$

of $E^{(J/\psi)} \cong 1.4$ of J/ψ photoproduction relative to ρ^0 production at $Q^2 \simeq M^2_{J/\psi}$, and an enhancement of $E^{(\Upsilon)} \cong 2.7$ for Υ photoproduction relative to ρ^0 production at $Q^2 \cong M^2_{\Upsilon}$, consistent with experimental results [12]. Concerning the energy dependence, in Fig. 2, we show the GVD-CDP prediction [11] for $\delta^{(V)}$, where our results are adapted to the experimentalists'

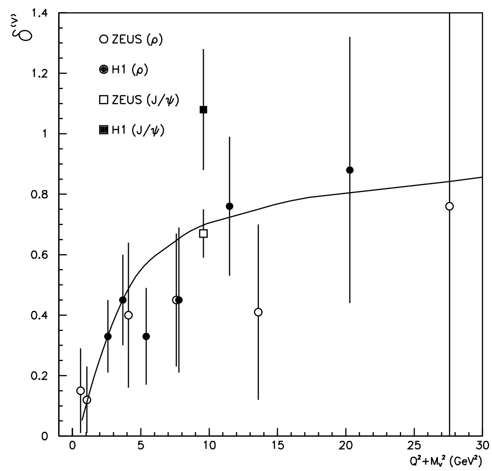

Fig. 2. The exponent $\delta^{(V)}$ in a parameterization of the energy-dependence of the experimental cross section by $W^{\delta^{(V)}(Q^2+M_V^2)}$ compared with the predictions from the QCD-based GVD-CDP.

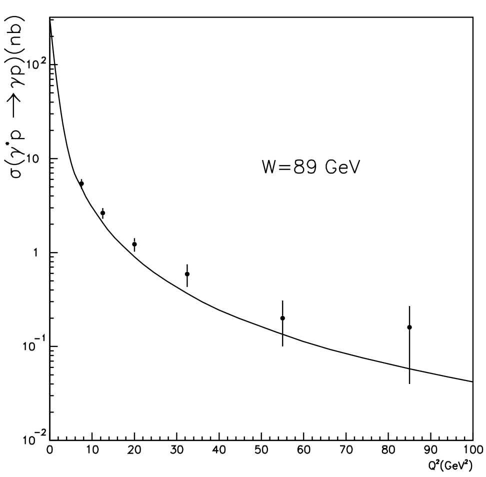

Fig. 3. The Q^2 dependence of DVCS at the energy of $W = 89$ GeV compared with the predictions from the QCD-based GVD-CDP.

fits of the form $W^{\delta(V)}$. Finally, in Fig. 3, we show our parameter-free predictions [11] for the Q^2 dependence of DVCS compared with HERA data [13]. We note that the theoretical results in Fig. 3 are based on a Q^2 — independent slope, b. The more realistic assumption of a Q^2 — dependent slope that decreases with increasing Q^2 by approximately a factor 2 in the range of Q^2 shown in Fig. 3, leads to improved agreement between theory and experiment.

After many years of experimental and theoretical efforts, a coherent picture of DIS, DVCS and vector-meson production in the low-x region has emerged for all $Q^2 \geq 0$. The Q^2 dependence and the relative normalization of the cross sections is well understood from the QCD-based GVD-CDP. The scale of the transition from a hard to a soft energy dependence is provided by $\Lambda^2(W^2)$, where $\Lambda^2(W^2)/6$ is identified with the effective gluon transverse momentum. The ab initio prediction of the power of W^2 in $\Lambda^2(W^2)$ is beyond the scope of our present understanding.

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