Production of vector mesons by real and virtual photons at high energies

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Abstract

A model based on Reggeon field theory is used for the description of the photo- and electroproduction of vector mesons $(\rho^0, \omega, \phi, J/\psi)$ on the proton. Its main feature is the dependence of the Pomeron intercept on the virtuality of the photon. The few parameters of the model were determined by fitting the total cross sections for real and virtual photons on the proton. This allows a parameter-free description of the energy dependence of vector meson production. Very good agreement with the existing high energy data is obtained.

The study of the production of vector mesons $(\rho^0, \omega, \phi, J/\psi)$ by real and virtual photons at high energies provides important information on the diffractive mechanism at very high energies. In particular, it allows to study the transition from the nonperturbative regime at low values of Q^2, the negative of the four momentum of the photon squared, to the perturbative regime at large Q^2. Many recent papers [1–6] have addressed the problem of the production of vector mesons. It was mainly described by the exchange of a 'soft' Pomeron [1,2]. At large Q^2 this reaction was seen as a test of perturbative QCD and of the exchange of the so-called 'BFKL Pomeron' [3–6]. The new HERA data [7,8] showed a nontrivial energy dependence of the production of ρ^0 and ψ mesons. The photoproduction cross section for ρ^0 mesons increases slowly with energy, consistent with the soft Pomeron model of Ref. [1] . However, at high Q^2 the increase is much faster than predicted by

this model. This faster increase with energy is also seen for the production of J/ψ-mesons. How these high Q^2 data agree with the perturbative approach or the BFKL model is not certain yet.

In this note we extend the approach in Ref. [9] to the production of vector mesons. This model was proposed for the description of the total cross section for the absorption of real and virtual photons at high energies. The central idea is that the Pomeron singularity, which governs the high energy behavior of the diffractive process, is not a simple pole characterized by a fixed intercept at $t = 0$, $\alpha_P(0)$. Instead, multiple Pomeron exchanges must also be considered, leading to modifications of the simple pole picture. These multiple exchanges are especially important for the 'supercritical' Pomeron, i.e., when $\Delta = \alpha_P(0) - 1 > 0$. Single as well as multiple Pomeron exchange are actually needed to obtain an amplitude satisfying the requirements of unitarity. Diagrammatic techniques for

Reggeon exchanges [10] and the AGK cutting rules [11] allow one to calculate the contributions of many such Pomeron exchanges to the scattering amplitudes and relate them to the properties of multiparticle production. Extensive phenomenological studies based on this principle (see, e.g., Refs. [12,13]) have shown that all data on soft hadronic interactions can successfully be described. It follows from these analyses that the observed intercept, $\alpha_P^{\text{eff}}(0) = 1.08$, which characterizes the energy dependence of hadronic cross sections in the currently available range of energies, $\sigma_{hp}^{\text{tot}} \sim s^{\alpha_P^{\text{eff}}(0)-1}$, is substantially smaller than the intercept, $\alpha_P(0)$, of the single Pomeron pole itself. In the studies [12,13] which take into account sequential ('eikonal') many Pomeron exchanges, one finds $\alpha_P(0) = 1.12$–1.15. Taking into account a more complete set of diagrams, which also include interactions among the exchanged Pomerons, an even larger intercept of $\alpha_P(0) \approx 1.2$ for the single pole is obtained [14]. So the *effective* intercept, which determines the overall energy dependence of the scattering amplitude, is due to the contribution from the single Pomeron exchange as well as of the Pomeron cuts, the exchanges of many Pomerons. It was argued in Ref. [9] that the relative importance of these cuts strongly decreases with the virtuality. In an electromagnetic reaction, real photons probe the entire complex of single and multiple Pomeron exchanges. However, with higher virtuality the space-time resolution increases and one 'sees' the single Pomeron exchange. This means that the intercept depends on Q^2, i.e., $\alpha_P^{\text{eff}}(0, Q^2)$. The exponent that governs the energy dependence of the total photon cross section thus also changes with Q^2, $\alpha_P^{\text{eff}}(0, Q^2) - 1 \equiv \Delta^{\text{eff}}(Q^2)$. For real photons, at $Q^2 = 0$, it has the value $\Delta^{\text{eff}}(0) \approx 0.08$ which also governs the soft hadronic interactions. At high Q^2, $Q^2 \gg 1$ GeV^2, we expect $\Delta^{\text{eff}} \approx 0.24$ due to the Pomeron pole. The parametrization chosen in Ref. [9] was therefore

$$\Delta^{\text{eff}}(Q^2) = \Delta(0) \left(1 + \frac{2Q^2}{d + Q^2}\right), \qquad (1)$$

with $\Delta(0) = 0.077$ and $d = 1.117$ GeV^2. At larger values of Q^2 it is necessary to take into account effects due to QCD evolution, which lead to an additional increase of the energy dependence with Q^2. Of course this simple parametrization of the complicated sum of a Pomeron pole and cuts is only an approximation.

Based on model calculations [15] it can be expected to work reasonably well up to high energies and certainly for the HERA kinematics. A further comparison of the approach used here with the model where a soft Pomeron pole and possibly also separate perturbative 'hard' Pomeron are exchanged [1–6] can be found in Ref. [16].

The approach sketched above was applied to the electromagnetic structure function of the nucleon [9] and we compare it here to the new H1 data [20]. For values of Q^2 above 2 GeV^2 perturbative QCD evolution was applied on the two loop level. For the virtual photon-proton total cross section the convention is adopted that

$$\sigma_{\gamma^* p} = \frac{4\pi^2 \alpha_{\text{EM}}}{Q^2(1-x)} F_2(x, Q^2), \qquad (2)$$

where x is related to the total centre-of-mass (CM) energy W by

$$W^2 \equiv s = \frac{Q^2}{x}(1 - x) + m_p^2, \qquad (3)$$

with m_p the mass of the proton. The results of the model from Ref. [9] are shown in Fig. 1, together with the predictions for the new H1 data. The agreement with the combined experimental data is excellent. The steady increase of Δ^{eff} with Q^2 is clearly seen. As the Q^2 dependence of Δ^{eff} dies off with increasing virtuality in this model, the change in slope for values of $Q^2 \gg d$ is due to the QCD evolution. We also show a cross section for a low virtuality, $Q^2 = 0.35$ GeV^2, which can be compared with the forthcoming data from E665. The preliminary data [21] indicate that our model also works very well in the kinematical range covered by E665.

The same approach can be used for other diffractive processes, such as the production of vector mesons by real as well as virtual photons, $\gamma^{(*)} p \rightarrow Vp$. There is however an important difference between exclusive processes such as vector meson production and inclusive diffraction dissociation. At large Q^2 QCD-evolution effects are important for single vector mesons production [5,6], while for inclusive diffraction the Pomeron is always in the 'soft' regime [17]. The combined contribution of the Pomeron pole and the cuts to the amplitude of the vector mesons production in the region of not very large Q^2 can be written in the following form:
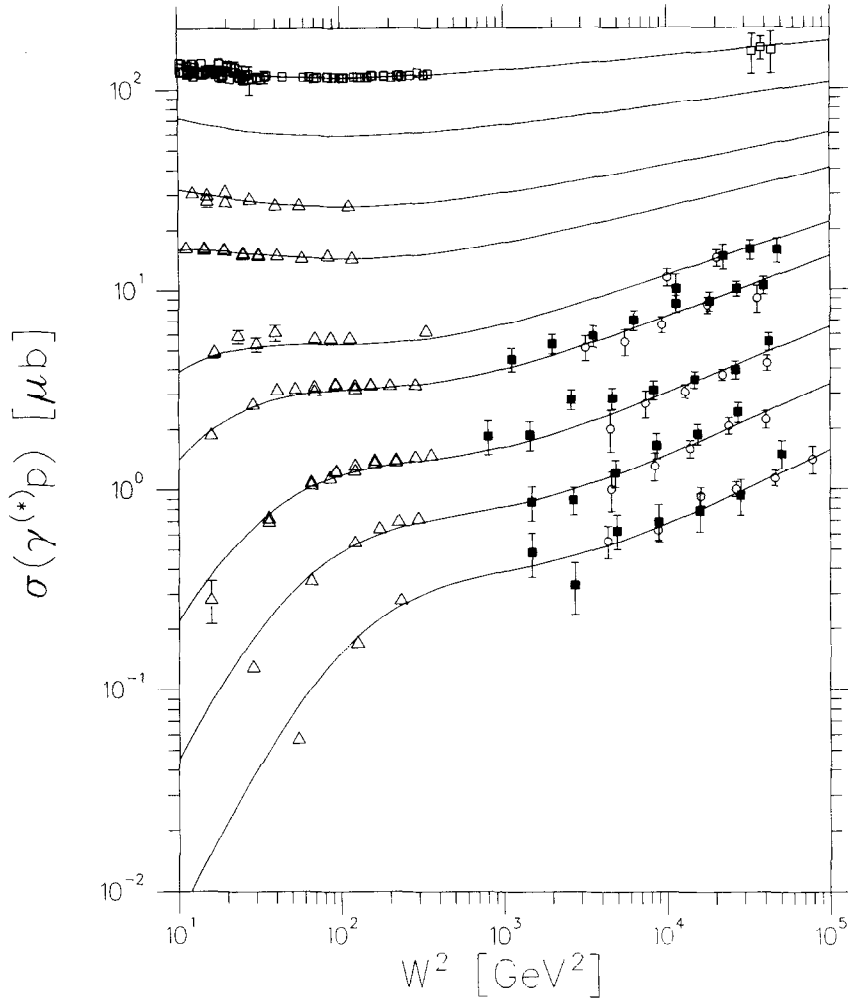
Fig. 1. The total cross sections for real and virtual photons for the proton obtained from the model of Ref. [9]. Reading from top to bottom the curves belong to $Q^2 = 0$, 0.35, 1.4, 3, 8.5, 15, 35, 65, 125 GeV^2. The H1 data [20] are denoted by the black squares, the ZEUS data by the open circles and the low energy data from BCDMS, SLAC and NMC (A compilation of F_2 data from BCDMS, NMC, SLAC and ZEUS can be found, e.g., in Refs. [9,20].) by the open triangles. The real photon data [18,19] are indicated by the open squares.

$$T(s, t, Q^2, m_V^2)$$

$$= f(Q^2, m_V^2, t) \left(\frac{s}{s_0}\right)^{\alpha_P^{\text{eff}}(t, \bar{Q}^2)} \eta(\alpha_P^{\text{eff}}), \qquad (4)$$

where $\eta(\alpha)$ is the signature factor and the dependence on the total CM-energy is determined by the effective Pomeron trajectory with $\alpha_P^{\text{eff}}(t, \bar{Q}^2)$. We have indicated through the argument $\bar{Q}^2$ that this effective parameter depends on the characteristic virtuality of the process. For the production of states made up of light quarks (u, d, s) we have $\bar{Q}^2 = Q^2$, while for vector

mesons made up of heavy quarks we choose

$$\bar{Q}^2 = c \, m_q^2 + Q^2, \qquad (5)$$

where m_q is the mass of the heavy quark and $c \sim 1$. In this way we take into account that for production of states made up of heavy quarks the contribution of cuts is small already at low Q^2. As mainly small values of t contribute to the total cross section for vector meson production, the effective Pomeron trajectory $\alpha_P^{\text{eff}}(t, \bar{Q}^2)$ is taken to be linear,
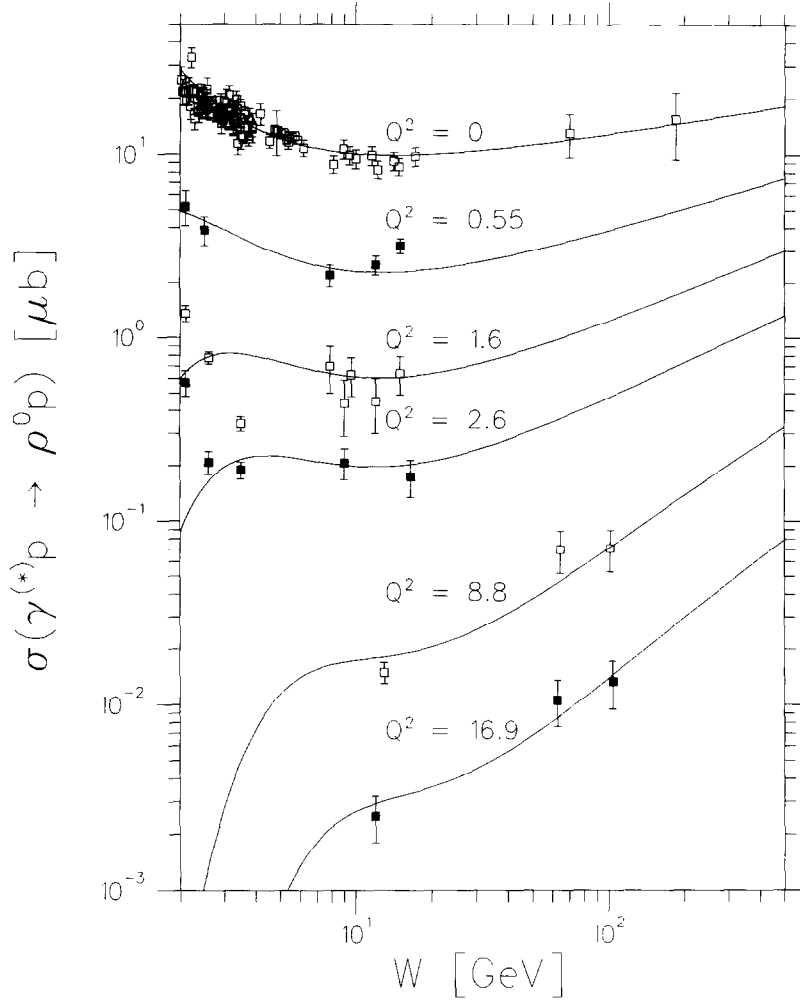
Fig. 2. The $\gamma^* p \rightarrow \rho^0 p$ cross sections for several values of Q^2 obtained from our model. The data for $W > 50$ GeV at high Q^2 are the recent ZEUS data. All data are from Ref. [7] and references therein.

$$\alpha_P^{\text{eff}}(t, \bar{Q}^2) = 1 + \Delta^{\text{eff}}(\bar{Q}^2) + \alpha_P' t , \qquad (6)$$

with the same parametrization for $\Delta^{\text{eff}}(\bar{Q}^2)$, Eq. (1), as in the structure function of the proton in Ref. [9]. We take $\alpha_P' = 0.25$ GeV^{-2}, which was obtained from the analysis of hadronic interactions. In principle α_P' also depends on $\bar{Q}^2$, but from analysis of elastic hadronic reactions it follows that this dependence is rather weak and can be neglected when discussing the energy dependence of the cross section. The t-dependence of the function $f(Q^2, m_V^2, t)$ is well known from, e.g., proton scattering, πN scattering and the production of ρ^0 mesons on the proton at low

energies. It is taken to be exponential [1],

$$f(Q^2, m_V^2, t) = \tilde{f}(Q^2, m_V^2) \exp(R^2 t) , \qquad (7)$$

with $R^2 = R_p^2 + R_V^2(Q^2)$ where

$$R_V^2 = \frac{R_{0V}^2 m_\rho^2}{m_V^2 + Q^2} ,$$

$$R_p^2 = 2 \text{ GeV}^{-2}, \qquad R_{0V}^2 = R_\rho^2 = 1 \text{ GeV}^{-2} . \qquad (8)$$

It has a factorizable form and takes into account the change with Q^2 and m_V^2 of the radius of the γVP vertex.
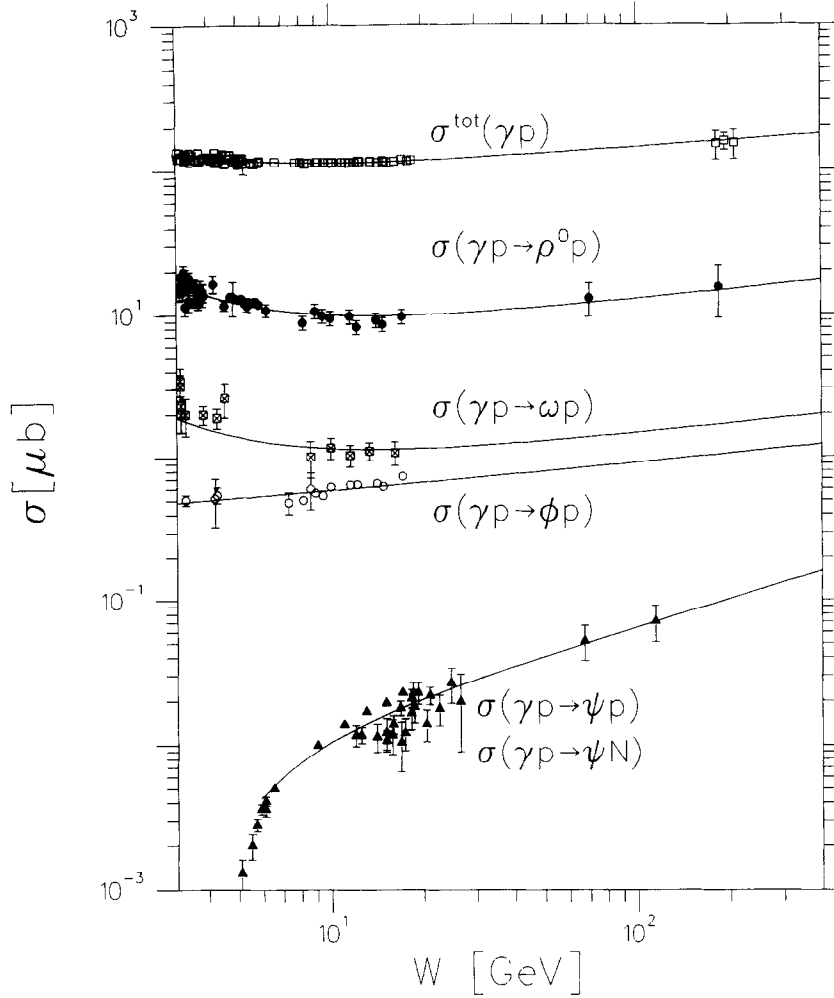
Fig. 3. A compilation of total photoproduction and vector meson production cross sections resulting from the model. The high energy data are from Refs. [7,8,19]. The low energy data are from Ref. [18] and references in Ref. [8].

The contribution of the Pomeron to the differential cross section for the $\gamma^{(*)}p \rightarrow Vp$ reaction then becomes

$$\frac{d\sigma}{dt} = \frac{1}{16\pi s^2}|T(s,t,Q^2,m_V^2)|^2$$

$$= \mathcal{F}(Q^2,m_V^2)\left(\frac{s}{s_0}\right)^{2\Delta^{\text{eff}}(\bar{Q}^2)}\exp[\Lambda(s)t], \quad (9)$$

where

$$\mathcal{F}(Q^2,m_V^2) = \frac{|\tilde{f}(q^2,m_V^2)\eta(\alpha_P)|^2}{16\pi} \quad (10)$$

and

$$\Lambda(s) = 2\left[R^2 + \alpha_P'\ln\left(\frac{s}{s_0}\right)\right] \quad (11)$$

is the slope of the diffraction cone. For the scale factor, s_0, we choose $s_0 = m_V^2 + Q^2$. This can be done, since the function $\mathcal{F}(Q^2,m_V^2)$ is unknown and will be fitted to the data. The dependence on the energy s is however entirely determined from Eqs. (1) and (9). In Ref. [9], the x-dependence of the structure function $F_2(x,Q^2)$ for very low x was parametrized as $x^{-\Delta^{\text{eff}}}$. For $s \gg \bar{Q}^2$ the energy dependence of the

cross section can therefore be expressed as

$$\frac{d\sigma}{dt} = \Phi(Q^2, m_V^2) F_{2,p}^{sea}(x, \bar{Q}^2)^2 \exp[\Lambda(s)t], \qquad (12)$$

where $F_{2,p}^{sea}(x, \bar{Q}^2)$ is the sea quark contribution to the structure function of the proton [9] with $x = \bar{Q}^2/(\bar{Q}^2 + s)$. The unknown dependence on Q^2 and m_V has been lumped into the function Φ, which at fixed Q^2 and for a given vector meson is simply a scale factor. Eq. (12) allows us to include perturbative QCD corrections, which are important at large values of Q^2, by applying the QCD evolution equations to the structure function. For the production of vector mesons made up of u and d quarks (ρ^0, ω), at not too large energies also secondary exchanges – the f and A_2 Regge poles – contribute in addition to the Pomeron exchange. In the parametrization of the structure function $F_2^p(x, Q^2)$ in Ref. [9] they correspond to the valence quark contribution. In the following we shall assume that for (ρ^0, ω)-production the ratio of the Pomeron to secondary exchanges is the same as for the structure function. This means that the entire structure function F_2^p as parametrized in Ref. [9] enters into Eq. (12) for vector meson production.

Results for the total cross section for the reaction $\gamma^* p \rightarrow \rho^0 p$, obtained by integrating Eq. (12) over t, are shown in Fig. 2. The t-dependence predicted in Eqs. (9) and (11) agrees with the slope parameter of 5.1 ± 1.5 in Ref. [7]. At each value of Q^2, the curves are normalized to obtain a good fit to the data. For energies where we expect our Reggeon-based model to apply, $s > 10\ \text{GeV}^2$, the data are described well. Especially the strong increase of the cross section with energy that was observed by the ZEUS Collaboration [7] at $Q^2 \sim 10\ \text{GeV}^2$ is well reproduced by the model. It will be interesting to test the model predictions for high energies, in particular at lower values of Q^2.

The data for ω-meson photoproduction are shown in Fig. 3. Only relatively low energy data are available and their W dependence is well described. For the photoproduction of ϕ and J/ψ mesons there is no valence quark contribution and only Pomeron exchange contributes to the amplitude. Using for the charmed quark mass $m_c^2 = 2.6\ \text{GeV}^2$, we obtain good agreement with recent HERA results [8] as shown in Fig. 3. The energy dependence of the ϕ meson is weaker and is also well reproduced by the model.

The few parameters of the model which we used here were fit independently to the data for the total cross section for real and virtual photons on the proton. In contrast to other parametrizations of these data, we showed that our parametrization can correctly predict the energy dependence of the total cross section for both photo- and electroproduction of vector mesons. The good fit of the vector meson data might be seen as further support for the underlying idea of the multiple Pomeron exchange and for the universality of the effective Pomeron intercept for all elastic-like reactions. The steady change of the effective intercept reflects the complex structure of the exchange – pole and cut contributions – which is probed with different space-time resolution as Q^2 changes. It will be interesting to see if the energy dependence of other diffractive processes in photo- or electroproduction at high energies can be described in a unified fashion by the same model.

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