J/ψ photoproduction at DESY HERA

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We revise and update an earlier model for J/ψ photoproduction based on a dipole Pomeron exchange. We show that the H1 and ZEUS experimental data reported recently can be well fitted by a soft Pomeron alone.

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In this paper we explore further the idea about the "softness" of heavy vector meson photoproduction put forward in a previous publication [1]. The basic assumptions are:

(1) Photoproduction of heavy vector mesons is a soft process. It can be described by the exchange of either a supercritical Pomeron with a low intercept, typically $\alpha_{\mathbb{P}}(0)-1\approx 0.08$, or a dipole one with a unit intercept. We stick to the second possibility since it gives better fits to the data. We remind the reader that the dipole Pomeron produces (logarithmically) rising cross sections even at a unity intercept of the trajectory, $\alpha_{\mathbb{P}}(t=0)=1$ (see Refs. [1,2] and references therein).

(2) The Pomeron—whatever it may be—contains more than just a single (and thus factorizable) term. The simplest and natural choice is a sum of a constant and a (moderately) rising term. Their interference leads [1,2] to the delay in reaching the asymptotics of $\sigma_{el}(s)$, observed at the DESY ep collider HERA. In other words, the relatively rapid increase of $\sigma_{el}(s)$ in the intermediate energy region of HERA is a transitory effect, followed by a subsequent slow down. Of course, the presence of more than one term in the Pomeron will break factorization (to be restored asymptotically).

(3) The $\gamma\mathbb{P}V$ vertex, shown as $\beta_2(t)$ in Fig. 1, may have a t-dependence different from that in a typical hadronic vertex. This deviation reflects the departure from vector meson dominance in the case of heavy mesons. Following the arguments presented in Ref. [1], we add in this vertex a term proportional to t and thus vanishing towards $t=0$. Its presence can make the determination of the slope parameter somewhat independent of the actual value of the total and differential cross section in the forward direction. The role of this term will be determined from the fits to the data.

(4) The Pomeron trajectory is not a linear function. This is a direct consequence of the theory (analyticity and unitarity) and it has been verified in many reactions—elastic and inelastic [3]. A reasonable model for the trajectory, compatible with the asymptotic bounds, yet feasible phenomenologically, is [4]

$$\alpha_{\mathbb{P}}(t)=1+\gamma(\sqrt{t_0}-\sqrt{t_0-t}). \quad (1)$$

In the present paper we concentrate on J/ψ photoproduction in the HERA kinematical region. This process is particularly advantageous in checking Pomeron models since, on one hand, due to the OZI rule [5], contributions from secondary trajectories here can be completely neglected, and, on the other hand, a lot of experimental data has been accumulated—much more than e.g. in the case of Υ photoproduction. This is the main reason why this reaction has recently received so much attention [6].

We use the following notation: the square of the center of mass system (c.m.s.) energy and the momentum transfer to the proton are, respectively,

$$W^2=s=(q+P)^2, \quad t=(P-P')^2 \quad (2)$$

with

$$|t|_{min}\approx m_p^2\frac{(M_V^2+Q^2)^2}{W^4}. \quad (3)$$

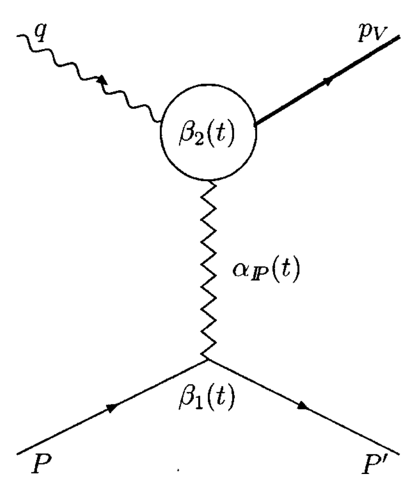

FIG. 1. Elastic photoproduction with an inelastic $\gamma\mathbb{P}V$ vertex. The wiggly line represents the dipole Pomeron. The diagram corresponds to the sum of two diagrams, i.e. one with a simple and the other with a double pole exchange.

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Here M_V is the vector-meson mass, m_p is the proton mass and $Q^2=-q^2$ is the photon virtuality. Let us note that at HERA one has $20\ \text{GeV}<W<240\ \text{GeV}$, $-13\ \text{GeV}^2<t<-10^{-4}\ \text{GeV}^2$.

We shall be particularly interested in the interpretation of the latest, highest-energy data, those published by the H1 Collaboration [7,8] and those reported by the ZEUS Collaboration at the 2000 Osaka Conference [9]. In our opinion these new data may become critical in discriminating between models for the Pomeron; in particular, they may be indicative of the presence of any hard component in J/ψ photoproduction [10].

Following these preliminary remarks, we write the scattering amplitude for the reaction $\gamma p \rightarrow J/\psi\ p$ as

$$A(s,t) \propto [a \exp(bt) + ct \exp(dt)] \left(\frac{s}{s_0}\right)^{\alpha_{\mathrm{P}}(t)} \times \left[\ln\left(\frac{s}{s_0}\right) + g - \frac{i\pi}{2}\right] \xi(\alpha_{\mathrm{P}}(t) P), \tag{4}$$

where $\xi(\alpha_{\mathrm{P}}(t)) = \exp(-i\pi\alpha_{\mathrm{P}}(t)/2)$. In Eq. (4), the residue [the first factor in the right-hand side(RHS)]) is a generalization of that used in Ref. [1], $\exp(bt)(1+ct)$. Actually, this residue is not exactly the product of the two vertices $\beta_1(t)$ and $\beta_2(t)$ (see Fig. 1), since the amplitude is a sum of two terms, each with its vertices. The second parentheses contains terms typical of a dipole Pomeron (see Refs. [1,2] and references therein): a constant, a logarithmically rising one and an imaginary part, coming from the signature factor. We are using a Pomeron trajectory of the form (1) with $t_0 = 4m_\pi^2$ and set $\gamma = m_\pi/(1\ \text{GeV}^2)$ to get the "standard" value for the Pomeron slope, $\alpha'_{\mathrm{P}}(0) \approx 0.25\ \text{GeV}^{-2}$.

We have calculated the elastic differential cross section of J/ψ photoproduction according to the formula

$$\frac{d\sigma}{dt} = [a \exp(bt) + ct \exp(dt)]^2 \left(\frac{s}{s_0}\right)^{2\alpha_{\mathrm{P}}(t)-2} \times \left[\left(\ln\left(\frac{s}{s_0}\right) + g\right)^2 + \frac{\pi^2}{4}\right] \tag{5}$$

and have fitted it to the recent H1 [7,8] and ZEUS [11] data.

With the parameters obtained from the fits to the differential cross section, the integrated elastic cross section

$$\sigma_{el}(s) = \int_{t_+}^{t_-} dt \frac{d\sigma}{dt}, \tag{6}$$

where $t_- = O[1/s^2] \sim 0$ and $t_+ \sim -s$, as well as the local slope of the differential cross section for various fixed values of t,

$$B(s) = \frac{d}{dt}\left(\ln \frac{d\sigma}{dt}\right), \tag{7}$$

were calculated.

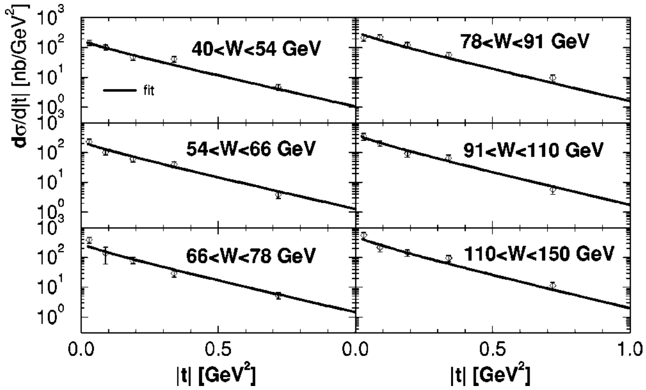

FIG. 2. Differential cross sections $d\sigma/dt[\text{nb/GeV}^2]$ for elastic J/ψ photoproduction for different bins of W. Data are from H1 [7]. The solid lines represent the result of the fit.

Setting $s_0 = 1\ \text{GeV}^2$, we fitted Eq. (5) separately to the H1 [7,8] data and the preliminary ZEUS data [11], presented at the 2000 Osaka Conference [9], since the two sets of the data differ substantially.

When fitting Eq. (5) to the H1 data, we found a wide region in the space of parameters where the χ^2/DOF is lower than 1. In order to remedy this ambiguity, we have chosen a set of parameters which leads to a $\sigma_{el}(s)$ close to the data points quoted by the H1 Collaboration [7,8]. For this purpose, we were constrained to fix a subset of parameters, namely a,b and c, and to leave free the remaining two. In this way we found a minimum with $\chi^2/\text{DOF} = 0.96$. We call, however, that $\sigma_{el}(s)$ does not result from direct measurements, but is always model-dependent.

The values of the parameters are: $a = 5.203\ \text{nb}^{1/2}\ \text{GeV}^{-1}$, $b = 2.086\ \text{GeV}^{-2}$, $c = -2.838\ \text{nb}^{1/2}\ \text{GeV}^{-2}$, $d = (2.343 \pm 0.351)\ \text{GeV}^{-2}$ and $g = -5.736 \pm 0.100$. Figure 2 shows the curve for $d\sigma/dt$ resulting from the fit, together with the H1 data points [7].

The elastic cross section $\sigma_{el}(s)$, obtained from our model, is compared in Fig. 3 with the H1 data points [7,8]. Note that the high-energy part of the theoretical curve does not tend to "harden" (the rate of its rise is even slowing down).

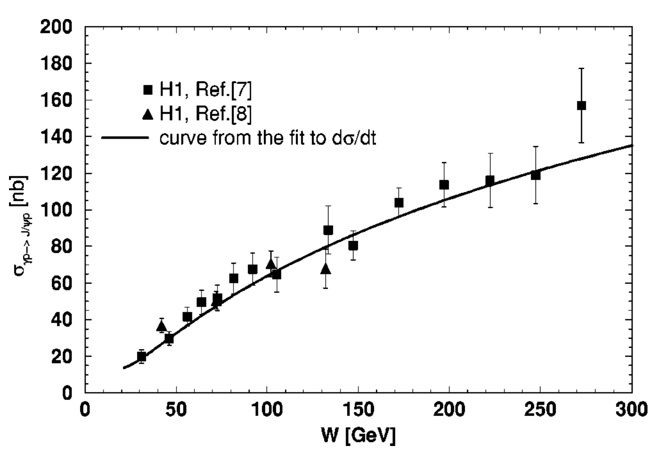

FIG. 3. Elastic J/ψ photoproduction cross section [nb]. Data are from H1 [7,8]. The solid line represents the result of the fit to the differential cross sections $d\sigma/dt$.

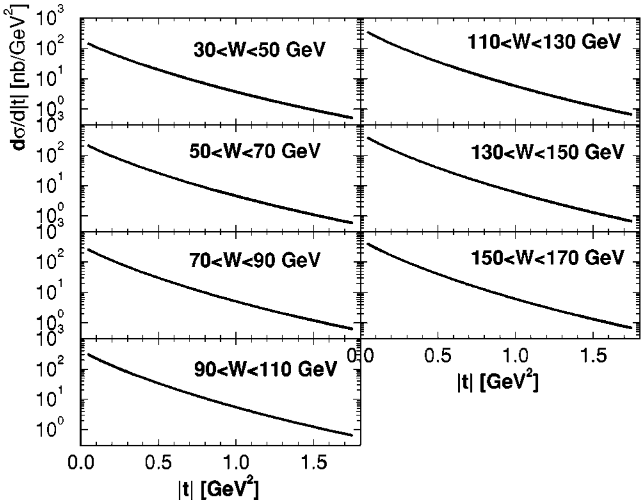

FIG. 4. The solid lines represent the result of the fit to the ZEUS data [11] for the differential cross sections $d\sigma/dt$[nb/GeV^2] for elastic J/ψ photoproduction, for different bins of W.

Our fit to the ZEUS data on $d\sigma/dt$ [11], on the other hand, is unambiguous. After noticing that d varies little in the fit, we have fixed its value, thus leaving only four parameters free. We set $d=0.851$ GeV^{-2}, the values of the fitted parameters being $a=(3.856\pm0.174)$ nb$^{1/2}$ GeV^{-1}, $b=(1.625\pm0.091)$ GeV^{-2}, $c=(-0.936\pm0.144)$ nb$^{1/2}$ GeV^{-2}, and $g=-4.126\pm0.126$. The fit leads to a single, pronounced minimum with χ^2/DOF$=1.04$ and the resulting curves for $d\sigma/dt$, for different bins of W, are shown in Fig. 4. This figure should be compared with Fig. 5 of Ref. [9].

With the parameters obtained from the fit to the ZEUS data [11] on the differential cross section, the elastic cross section, $\sigma_{el}(s)$ has been calculated according to Eq. (6). The result is presented in Fig. 5. A comparison with Fig. 4 of Ref. [9] shows a very good agreement with the ZEUS data for $\sigma_{el}(s)$.

Finally, the behavior of the local slope $B(s)$, calculated from Eq. (7) as a function of s for various fixed values of t, is shown in Fig. 6. As expected from the differential cross

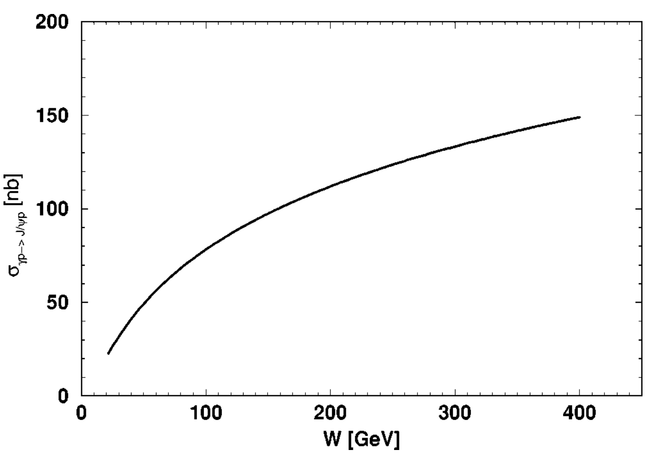

FIG. 5. The solid line represents the elastic J/ψ photoproduction cross section [nb], resulting from the fit to the ZEUS data [11] for $d\sigma/dt$.

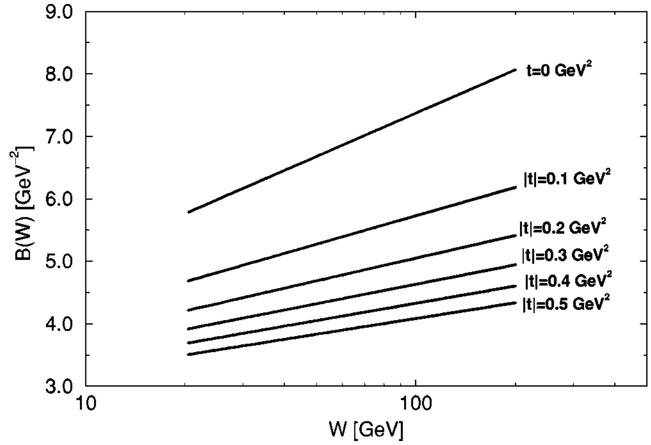

FIG. 6. Prediction from our fit to the ZEUS data for the slope B[GeV^{-2}].

section and the curvature of the Pomeron trajectory (1), the local slope decreases with $|t|$. Its value at $t\approx-0.3$ GeV^2 meets the experimental measurements (see Fig. 6 of Ref. [9]). This is quite understandable, since the experimental value is the average over a wide interval in t covering the measurements. The rise of the slope towards $t=0$ is a well-known phenomenon in hadronic physics; its appearance in photoproduction was emphasized e.g. in Ref. [12].

The reader should notice that the ZEUS data points [11] for $d\sigma/dt$, $\sigma_{el}(s)$ and $B(s)$ are not plotted in Figs. 4–6. The reason is that these data points are not yet published by the ZEUS Collaboration.

The main result of this paper is that J/ψ photoproduction is "soft." The highest-energy data [7,9] bring new evidence in favor of this observation. They show that the introduction of any "hard" term here is unnecessary.

This feature appears not only in the relative low, with respect to the "experimental data." value of $\sigma_{el}(s)$, but even more so in its downwards curvature, resulting from the presence of two terms in the amplitude, whose interference produces the rapid rise in $\sigma_{el}(s)$ in the mid-HERA energy region, with a subsequent slow down at high energies.

More information on the possible "hardening" of the Pomeron with increasing Q^2 may come from the extension of the present (or similar) models to electroproduction. However this is not easy since all (five, in our case) parameters will acquire some (complicated) Q^2 dependence, thus increasing the number of the fitted parameters and consequently reducing the credibility (confidence level) of the model and its fit. A possible solution may be suggested by QCD calculations of the upper vertex in Fig. 1, $\beta_2(t)$, for virtual photons.

Finally, let us mention that the dipole Pomeron was criticized [13] for the presence of a negative constant term in it that—according to the authors of Ref. [13]—implies a negative total cross section at low energies. Actually, this does not happen because of the presence of subasymptotic terms at low energies, compensating the negative contribution ($g=-5.736$, in the H1 case, $g=-4.126$, in the ZEUS case): a Pomeron daughter (for a purely diffractive process) and/or secondary Reggeons otherwise. Our fits have been made, however, well beyond the low energy region, where subasymptotic contributions may be important.

After the completion of this work we have become aware of similar conclusions drawn in a paper by Martynov, Predazzi, and Prokudin [14].

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