Eur. Phys. J. C 10, 461–467 (1999)
Digital Object Identifier (DOI) 10.1007/s100529900046

THE EUROPEAN PHYSICAL JOURNAL C

Photoproduction of heavy vector mesons at HERA – a test field for diffraction*

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Received: 11 January 1999 / Published online: 8 September 1999

Abstract. Exclusive diffractive photoproduction of heavy vector mesons (V=$\phi, J/\psi$, and Υ) at HERA is studied in a model employing a dipole Pomeron exchange (P) with an inelastic γPV vertex. The model is fitted to the data on $\mathrm{d}\sigma/\mathrm{d}t$, B, and σ_{el} for $Q^2 = 0$ and beyond the threshold region. The elastic cross sections for both ϕ and J/ψ photoproduction show a moderate increase within the HERA energy region. The flattening of the slope $B(s)$ (indicating little or no shrinkage) for J/ψ is not correlated with the slope of the Pomeron trajectory. Estimates for Υ photoproduction at HERA are given.

1 Introduction

Diffractive photoproduction, as well as electroproduction, of heavy vector mesons at HERA continues to attract the attention of both theorists and experimentalists (for a recent review, see, e.g., [1]–[3]; a comprehensive earlier review on this subject can be found in [4]) as a unique test field for diffraction, an interface between soft and hard physics, with three independent kinematical variables, the c.m.s. energy $W = \sqrt{s}$, the transferred momentum $\sqrt{-t}$ and the virtuality of the external particle(s) $Q^2 = -q^2$, involved simultaneously. High masses M_V of the external vector mesons are usually treated on the same footing as the photon virtuality, by introduction of the variable $\tilde{Q}^2 = Q^2 + M_V^2$, although M_V^2 should not be identified with Q^2. In the present paper we consider only photoproduction, i.e. $Q^2 = 0$.

An important reason why heavy vector mesons are particularly suitable to the study of diffraction is that, by the OZI rule [5], photoproduction of heavy vector mesons is mediated by the exchange of a Regge trajectory that has vacuum quantum numbers and is made of gluons (the Pomeron trajectory). In the case of the ϕ production, a small contribution from subleading, secondary Reggeons, due to the $\omega - \phi$ mixing, are also possible.

Physicists have been looking for reactions and/or kinematical regions with the Pomeron dominance (Pomeron filters) for a long time: for example, in the elastic scattering with exotic direct channels (as in K^+p or pp scattering) or in other reactions (mainly $\bar{p}p$) at very high energies. In the hadron scattering, however, genuine Pomeron filters cannot be completely realized, since even in the case of exotic channels a small contribution from secondary trajectories is inevitably present due to the breakdown of the exchange degeneracy. The alternative way to filter – by going to very high energies – is prevented by another, even lesser-known, object, the Odderon, a particle that obscures the picture and makes the discrimination ambiguous. In the case of photoproduction, only the positive C-parity exchange is allowed (the Odderon exchange is forbidden).

The application of the Regge-pole theory to photoproduction usually implies also the validity of vector meson dominance (VMD), by which the photon, before interacting with the proton by means of a Reggeon exchange, first fluctuates, becoming a vector meson (Fig. 1). The applicability of VMD and its generalizations to heavy-meson states have been recently discussed in a number of papers [6, 7].

An alternative to this typical Regge-pole model of photoproduction is perturbative QCD (PQCD). While PQCD calculations are efficient (see, e.g., [8]–[12]) in the evaluation of the upper vertex of Fig. 2, or of the proton structure function probed by a hard Pomeron and related to the imaginary part of the photoproduction forward scattering, they are less appropriate for studying the typically nonperturbative features of diffraction, such as the energy dependence of its slope, the t dependence (shape of the assumed cone), the cross sections, etc.

Recent studies [13] also involve – apart from the abovementioned measurable quantities – more subtle details,

* Work supported by the Ministero italiano dell'Università e della Ricerca Scientifica e Tecnologica and by the INTAS

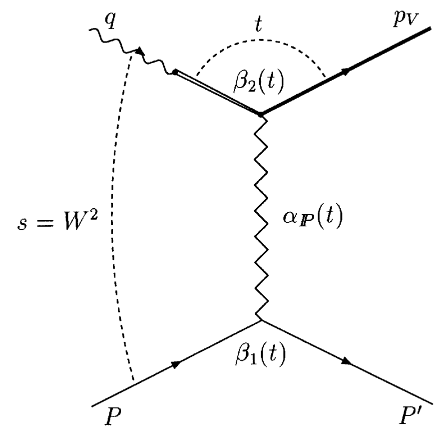

Fig. 1. Elastic photoproduction according to vector meson dominance

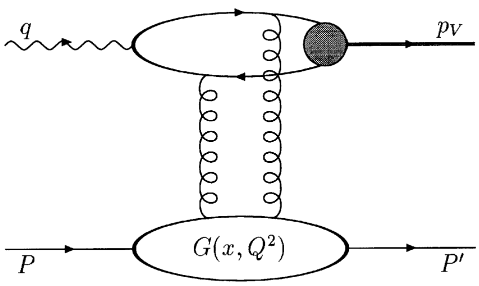

Fig. 2. Elastic photoproduction according to perturbative QCD

such as photoproduction of radially excited states, the helicity dependence, etc. In a different paper [14], a detailed analysis of the t dependence of the cone, including a possible dip–bump structure seen in hadronic reactions, was studied.

Most of the existing models rely on the so-called two-component picture, a compilation of the soft mechanism (see Fig. 1), essentially based on VMD and the Donnachie–Landshoff (DL) model of the Pomeron [15], and a hard one based on the PQCD calculation of the exchange of a pair of gluons coupled either to the quark–antiquark pair, as illustrated in Fig. 2, or the dipole picture [13] (not to be confused with the dipole Pomeron), where the nonperturbative effects from the propagator are plugged into the vertices. Apart from the peculiarities of the different models, a common result of all these approaches is a power increase in energy of the cross sections s^ϵ, fed in from the DL model, the fitted value ϵ being considered indicative of the hardness of diffraction. Another argument in favour of the hardness of diffraction at HERA, widely discussed now in the literature [16], is the apparent flatness (small or vanishing slope) of the Pomeron trajectory. Anticipating our forthcoming discussion, here we only notice that the Pomeron intercept is universal, independent of the virtuality or mass of the external particles; so the above-mentioned effect may have a different origin.

The aim of the present paper is to analyze the basic assumptions behind the existing models. To this end, we use a factorized model with a Pomeron exchange, combining Figs. 1 and 2, without specifying the details (VMD or PQCD) of the upper vertex. Instead, we consider a general form for the (inelastic) γPV vertex and a two-term Pomeron exchange (simple and double pole). By confronting the model with the data, we study its physical consequences.

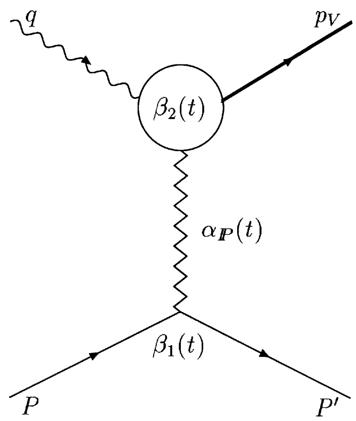

Fig. 3. Elastic photoproduction with an inelastic γPV vertex. The wiggly line, showing the Pomeron exchange, corresponds to a sum of two diagrams, i.e., simple- and double-pole exchanges

2 Kinematics and the HERA data

Here we introduce the kinematics and make several general comments concerning the HERA data from the ZEUS and H1 collaborations.

We use the standard notation for the reaction energy (see Fig. 3). The square of the c.m.s. energy and the momentum transfer to the proton are, respectively,

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

with

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

Here M_V is the vector-meson mass, m_p the proton mass and $Q^2 = -q^2$ the photon virtuality. Hereafter, we will use the symbol s to indicate W^2. At HERA one has 20 GeV $< W <$ 240 GeV, -13 GeV$^2 < t < - \mid t \mid_{\min}$, with $\mid t \mid_{\min} \approx 10^{-4}$ GeV negligibly small.

Since the differential cross section is the only directly observable quantity, $\sigma_{\rm el}$, as the slope B and other quantities are derivatives, its determination and interpretation is of great importance; small errors in $\mathrm{d}\sigma/\mathrm{d}t$ may be amplified in $\sigma_{\rm el}$ or in B. It should be admitted that the precision of the data is inferior to that in elastic hadron scattering. Therefore, in studying universal diffractive phenomena (such as the shape of the cone) or parameters (e.g., of the Pomeron trajectory) one should rely on the existing experience in hadronic (e.g., pp or $\bar{p}p$) scattering at high energies. In particular, two unmistakable structures superimposed on the nearly exponential cone are known to exist (see, e.g., [17,18]):

1. The "break", or change of the local slope at $t \approx -0.1$ GeV^2, due to the nearby 2-pion threshold in the unphysical region ($t > 0$), results in the sharpening of the cone (increase of $B(t)$ towards $t = 0$). This tiny effect is not yet observable at the level of statistics typical of the HERA measurements.

2. The dip–bump structure, clearly seen and thoroughly studied in hadronic reaction [17], is highly indicative of the diffractive phenomena. Its position, in general, is determined by the slope B and the amount of absorptions [17]. While the smaller slope (with respect to pp scattering) in the heavy-vector-meson production evidently pushes the dip outwards, the amount of absorptions is not well known (it is expected to have a countereffect on the position of the dip). More data are needed to reveal the existence of a dip, which would be an important step towards a better understanding of diffraction.

The apparent flattening of the cone in J/ψ photoproduction may seem an indication of a nonlinear Pomeron trajectory. Here again, the lesson from pp and $\bar{p}p$ scatterings may be useful. They tell us that the slope of the Pomeron trajectory [17], apart from the small $|t|$ curvature due to the lightest two-pion threshold in the cross channel of the amplitude, remains almost constant until about 1 GeV^2 – the neighbourhood of the dip. The nonlinearity of the (Pomeron) trajectory can be of fundamental importance at large $|t|$; however, the present HERA data are unlikely to tell us more about its details than the hadron-scattering data do. Instead, the form of the nonlinear Pomeron trajectory gained from pp and $\bar{p}p$ data may be used in identifying new effects at HERA.

Given the above-mentioned uncertainties, the formula

$$\sigma_{\mathrm{el}} = \frac{1}{B_{\mathrm{exp}}} \frac{d\sigma}{dt}\bigg|_{t=0} ,$$

where B_{exp} is the experimental value of the slope, may be the right approximation. Formally, it implies $B(t = 0)$, although the slope can be determined only with respect to a finite interval (bin) in t. In view of the apparent flattening of the cone and the uncertainties in the determination of $\mathrm{d}\sigma/\mathrm{d}t$, the choice of the relevant bins and the resulting B strongly influences the calculated σ_{el}. A reasonable way [13] to account for the above-mentioned effect of the "sharpening" of $\mathrm{d}\sigma/\mathrm{d}t$ towards $t = 0$ is by augmenting the measured B by 1 or 2 units of GeV^2. Since the determination of B is crucial for the dynamics of J/ψ production (see Fig. 4 and below), this point needs further clarification.

3 Diffraction and Regge-pole models

Factorization is a basic ingredient of any Regge-pole model (see [19]). Accordingly, the scattering amplitude corresponding to a simple Regge-pole exchange, up to a signature factor $\xi(t)$, is a product of two vertices $\beta_1(t)$, $\beta_2(t)$ and a propagator $(s/s_0)^{\alpha(t)}$ (see Fig. 1). If the amplitude is a sum of several exchanges (the Pomeron itself may be more than just a simple pole), then each term conserves its factorization properties separately.

The lower vertex in Fig. 1 is well known (from the pp and $\bar{p}p$ scattering) to be e^{bt} (the application of more involved forms is not relevant here), an estimate for b being [19] $b = 2.25$ GeV^{-2}. By factorization, the properties and values of the parameters in the Pomeron trajectory are universal and reaction-independent. Below we use the "canonical" value of $\alpha' = 0.25$ GeV^{-2} for the Pomeron slope. This input is sufficient to calculate the slope of the exponential cone:

$$B(s) = \frac{\mathrm{d}}{\mathrm{d}t} \ln \frac{d\sigma}{dt} \mid_{t=0} .$$

As a result, for the extreme case of a point-like coupling in the upper vertex, $b_2 = 0$,

$$B(s) = (4.5 + 0.5 \ln(s/s_0)) \text{ GeV}^{-2} , \qquad (1)$$

and one gets $B = 8.75$ GeV^{-2} at $W = 70$ GeV (with $s_0 = 1$ GeV^2) – much higher than what is found from the data. This value can be lowered by lowering b [20,21] (this is difficult, since the above value is already a conservative estimate), lowering α' (which is incompatible with factorization) and/or increasing s_0. The last option is acceptable, in fact demanded by the data on hadron scattering [17,18]. Although in the relevant fits the increase of s_0 is accompanied by a corresponding increase of b, the net effect for B from (1) remains nearly zero. Anyway, even the lower limit of B as given in (1), $B = 4.5$ GeV^{-2}, saturates the experimental value for the J/ψ photoproduction (see Fig. 4). In other words, in the simple Regge-pole model, there is no room left for the radius of a vector meson as heavy as J/ψ or Υ.

The next important issue is whether the Pomeron contribution can be adequately represented by a single pole exchange, as it is in the case of the DL model. If so, the total cross section is simply $\sigma_t \sim s^{\epsilon}$, and the elastic cross section is also a single power, $\sigma_{\mathrm{el}} \sim s^{\epsilon}$.

The original DL model was fitted to the data with two terms, the Pomeron and an effective contribution of subleading Reggeons. The latter effectively contains the low-energy background also (although this was never emphasized). The increasing part of the Pomeron should be added by a constant background, as follows from the empirical fits to the total cross sections [23,18,24], the structure functions and their evolution [25], or from nonperturbative QCD calculations [26].

To illustrate the aforesaid, let us write the Regge-dipole-scattering amplitude in a simple "geometrical" form (see [17]):

$$A(s,t) \sim R^2 \mathrm{e}^{R^2 t} ,$$

where $R^2 \equiv R^2(s) = \alpha'(b + L - \mathrm{i}\pi/2)$, $L \equiv \ln\left(\frac{s}{s_0}\right)$. The total cross section in this model is

$$\sigma_t \sim b + L,$$

while the elastic cross section grows as

$$\sigma_{\mathrm{el}} \sim \frac{(b+L)^2 + \pi^2/4}{b+L}$$

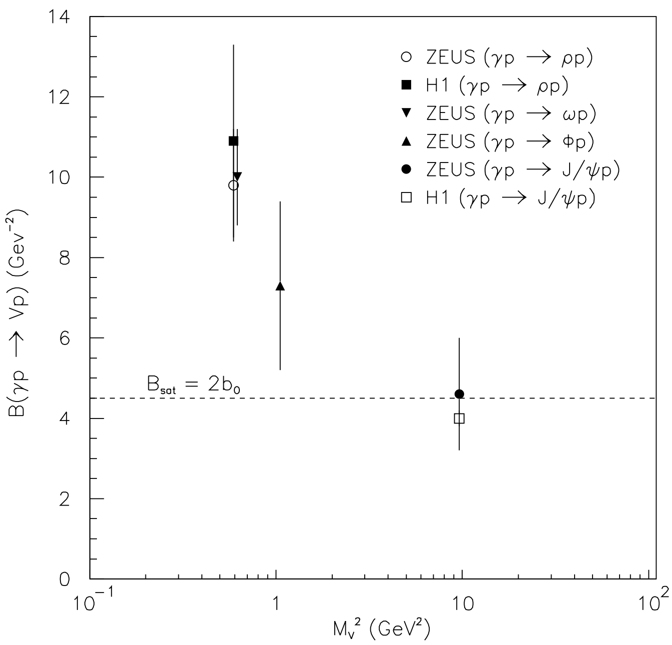

Fig. 4. The slope B versus the square M_V^2 of the mass of vector bosons. Existing experimental data converge, saturating at the minimal value given by the lower pPp vertex, $B = 4.5$ GeV^{-2}

and its asymptote is delayed with respect to a single rising term (e.g., a power or logarithm(s)). By this simple example (anticipating a more realistic model to be presented in the next section), we intend to demonstrate the importance role of a constant background to the rising term (whatever its form), and that the parametrizations of the HERA data by a single power W^ϵ may be oversimplified.

4 Dipole-Pomeron model of diffraction at HERA

We consider the reaction $\gamma p \to Vp$, where V stands for ϕ, J/ψ or Υ, in the framework of the Regge-pole model with a dipole Pomeron (DP for brevity) exchange in the t channel and inelastic γPV upper vertex shown in Fig. 3.

In the angular momentum plane, the partial wave amplitude corresponding to a Regge dipole is

$$a(j,t) = \frac{\beta(j,t)}{[j-\alpha(t)]^2} = \frac{\mathrm{d}}{\mathrm{d}\alpha(t)}\frac{\beta(j,t)}{j-\alpha(t)},$$

where the function $\beta(j)$ is t-independent and nonsingular at $j = \alpha(t)$.

The above derivative automatically produces a $\ln s$ term in the scattering amplitude; this provides for rising cross sections with the Pomeron intercept equal to one, and secures the unitarity bounds. Notice also that within Regge-type models, this is the fastest rise allowed by unitarity, since asymptotically $\sigma_t \leq B$ and the maximally allowed shrinkage here is $B \sim \ln s$.

The DP model was successively applied to hadronic reactions, describing both the s and t dependence (for a review of the DP model, see [17]). Around $W \sim 100$ GeV, the rate of increase of the cross sections is numerically close to that in the DL model, i.e., about $W^{2\epsilon}$, with $\epsilon \approx 0.08$, but conceptually, they are quite different. Furthermore, the interference between two terms, which can be interpreted as contributions from a simple and a double pole, produces a diffractive pattern in t, confirmed experimentally in hadronic reactions (see [17,18]).

In what follows, we apply the above concept to diffractive photoproduction of heavy mesons. Neglecting the spin, we write the invariant scattering amplitude corresponding to the exchange of a DP as

$$A(s,t) = \mathrm{i}(-\mathrm{i}s/s_0)^{\alpha(t)-1}\{G_1(t) + G_2(t)[\ln(s/s_0) - \mathrm{i}\pi/2]\}\,, \tag{2}$$

where

$$G_1(t) = A_1 \mathrm{e}^{bt}(1 + h_1 t) \tag{3}$$

and

$$G_2(t) = A_2 \mathrm{e}^{bt}(1 + h_2 t) - \gamma \tag{4}$$

are the residues of the simple and double pole, respectively. $G_1(t)$ factorizes (see, for instance, Fig. 3) into a standard pPp vertex, $\sim \mathrm{e}^{bt}$, with $b = 2.25$ GeV^{-2} determined from the pp scattering, and a γPV vertex, which we parametrize by a simple polynomial, with a free parameter h_1 to be fitted to the data. Were VMD applicable to the upper vertex, one would expect h_1 to be small and positive (the expansion of an exponential with a small slope (radius)). If however h_1 turns out to be negative, this will indicate departure from VMD with an increase of the upper vertex in $|t|$.

The residue of the double pole $G_2(t)$ may be cast from $G_1(t)$ by an integration (see [17]). Here we relax the rather stringent constraint that relates the values of A_2 to h_2 and A_1 to h_1, respectively, keeping only the integration constant γ as another free parameter. If that relation is confirmed by the data, it will be indicative of the hadronic nature of diffraction in photoproduction.

We use a simple linear trajectory for the Pomeron $\alpha(t) = 1 + 0.25t$. This linear trajectory may be replaced by a nonlinear one in future, more sophisticated fits to the data.

From (1) we get, for the elastic differential cross section,

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = (s/s_0)^{2\alpha(t)-2} \times \left[(G_1(t) + G_2(t)\ln(s/s_0))^2 + \frac{\pi^2}{4}G_2^2(t)\right]\,, \tag{5}$$

whence σ_{el} is calculated according to (see Sect. 2)

$$\sigma_e l = \frac{1}{B}\frac{\mathrm{d}\sigma}{\mathrm{d}t}\bigg|_{t=0}\,. \tag{6}$$

The s and t dependence of the slope B can be calculated from

$$B(s,t) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\ln\frac{d\sigma}{\mathrm{d}t}\right)\bigg|_{t=o} = 2\alpha'\ln(s/s_0) + N/D, \tag{7}$$

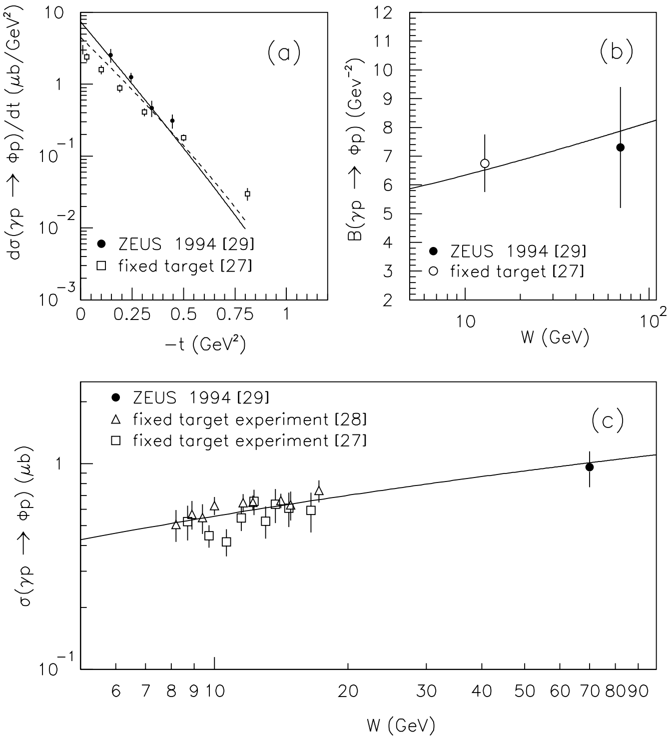

Fig. 5. ϕ photoproduction: **a** the differential cross section: the dotted line corresponds to the average energy $W = 13.3$ GeV and the full line to the average energy 70 GeV; **b** the slope parameter; **c** the elastic cross section. The data are taken from [27], [28] and [29]

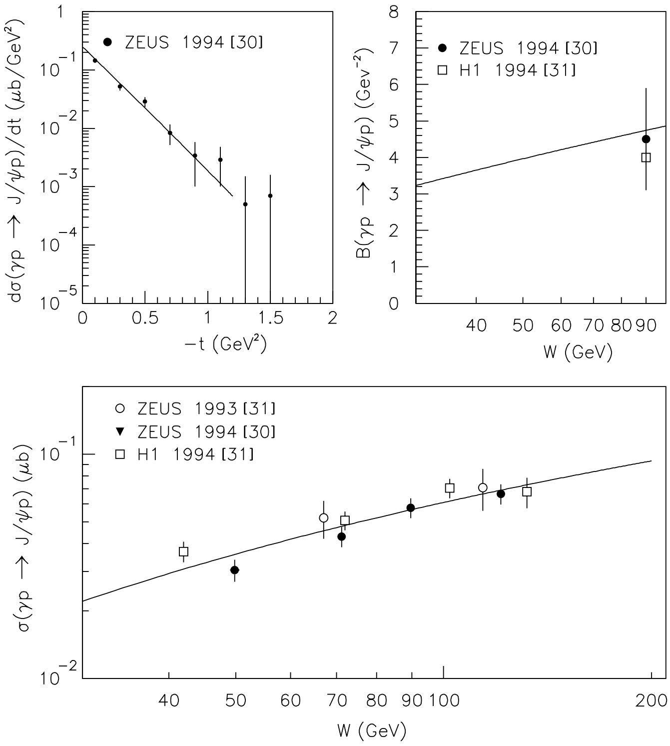

Fig. 6. J/ψ photoproduction: **a** the differential cross section; **b** the slope parameter; **c** the elastic cross section. The data are taken from [30] and [31]

where

$$N = 2\bigg([A_1 + (A_2 - \gamma)\ln(s/s_0)][A_1(b + h_1) + A_2(b + h_2)\ln(s/s_0)] + \frac{\pi^2}{4}(A_2 - \gamma)A_2(b + h_2)\bigg)$$

and

$$D = \frac{d\sigma}{dt}\,|_{t=0} = [A_1 + (A_2 - \gamma)\ln(s/s_0)]^2 + \frac{\pi^2}{4}(A_2 - \gamma)^2.$$

In calculating $\sigma_{\rm el}$ however we shall use the experimental value of the slope $B_{\rm exp}$.

5 Fits to the HERA data: Discussion of the results

To study the Pomeron behaviour by itself, unbiased by possible threshold effects, we impose lower bounds in energy: $W > 8$ GeV in the case of the ϕ photoproduction and $W > 30$ GeV in the case of the J/ψ photoproduction. As mentioned before, we consider only the case $Q^2 = 0$. The parameters to be fitted are A_1, A_2, h_1, h_2, and γ.

Figs. 5(a)–(c) show the differential and the integrated elastic cross sections as well as the slope parameter of the ϕ production fitted to the fixed target [27,28] and the HERA collider data [29]. The values of the fitted parameters turn out to be $A_1 = 1.9126\mu b, A_2 = 0.18203\mu b,\ h_1 = 0.85842\ \mathrm{GeV}^{-2},\ h_2 = 0$, and $s_0 = (8\ \mathrm{GeV})^2$.

Figs. 6(a)–(c) show the same quantities for the J/ψ photoproduction, with the following values for the fitted parameters: $A_1 = 0.27523\mu b, A_2 = 0.091278\mu b,\quad h_1 = -0.80606\ \mathrm{GeV}^{-2}, h_2 = 0$, and $s_0 = (30\ \mathrm{GeV})^2$. Here only the HERA data [29]–[31] were used to fit the parameters.

Some comments are in order. Throughout the fitting procedure, γ remains very small, so in order to reduce the number of the free parameters, we simply set $\gamma = 0$. Since this parameter determines the amount of absorptions (present in the model – see [17]) and the fate of a possible dip, this simplification is to be relaxed after a better understanding of the present approach (from the previous experience in hadronic scattering [17,18], γ is known to be small anyway).

Photoproduction of J/ψ requires the parameter h_1 to be negative. This is the effect of the “saturation” of the slope by the lower vertex only, visible in Fig. 4. To meet the data, the upper, inelastic vertex “subtracts” from the net slope. A negative value of h does not favour VMD, indicating a more complicated, inelastic structure in the upper vertex of Fig. 3.

We notice also that reasonable fits require large values of s_0, which increase with the mass of the produced vector meson. This parameter is correlated in some way with the external masses. Large values of $s_0 \sim 100\ \mathrm{GeV}^2$ are typical also for the hadronic reactions [17,18,33,34].

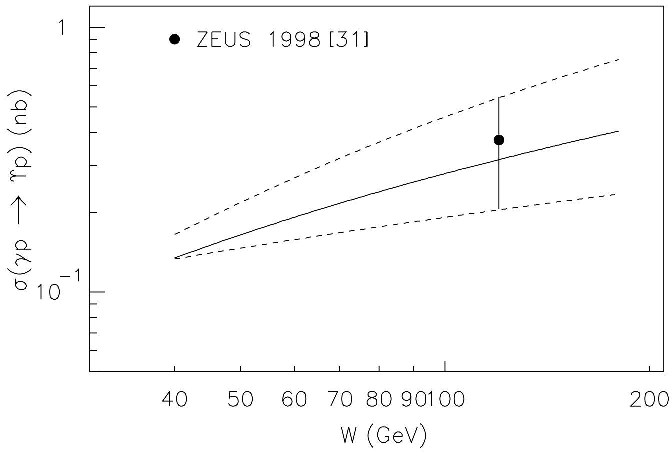

Fig. 7. A prediction for the elastic Υ photoproduction. The data point is taken from [32]

Let us now discuss some general features in the behaviour of the observables, as they follow from our model. Even though we use a linear Pomeron trajectory, the cone is not exactly exponential due to the interference of the two terms of the Pomeron. An important immediate consequence is that the apparent nonshrinkage (little or no s dependence in B) in the case of J/ψ may result from the interference of the simple and double poles. Otherwise stated, the form

$$\frac{d\sigma}{dt} = f(t) W^{[4\alpha(t)-4]}, \tag{8}$$

used in [16] to fit the Pomeron trajectory, causing the trajectory's apparent flatness, $\alpha' \approx 0$, is not unique (e.g., f may depend also on s). The flattening of $B(s)$, visible in Fig. 6(c), can be achieved with a universal Pomeron intercept, $\alpha' = 0.25\ \mathrm{GeV}^{-2}$ if, e.g., (5) is used instead of (8). Moreover, the flattening of the slope may be followed by an "antishrinkage" in Υ production (the negative, albeit small, value of α' in [16] could be a message indicating this trend).

The energy dependence of the elastic cross sections, shown in Figs. 5(a) and 6(a), is mild, and fits the data perfectly well. The large mass of J/ψ does not "harden" the dynamics, i.e., the rate of increase is similar to the case of its lighter counterpart ϕ. Moreover, the present increase corresponds to a transitory regime, preceding the asymptotic $\sim \ln s$ rise, to set up at still higher energies.

To make predictions, we try to establish regularities between the values of the fitted parameters. Since the radius of the heavier Υ is smaller than that of J/ψ, which is already near, or even below, the saturation value (see Fig. 4), the effect of the subtraction (negative value of h_1) in the case of Υ, is expected to be the same as, or even weaker than that in J/ψ. So it may be reasonable to choose $h_{1,2}$ to be the same as in J/ψ. The slope B in the Υ photoproduction is also expected to be equal to (or even slightly larger than) the saturation value, approximately $4.5\ \mathrm{GeV}^{-2}$. The parameter s_0 tends to rise as $\ln M_V^2$, so by extrapolation we choose $s_0 = (50\ \mathrm{GeV})^2$ for Υ production.

The relative normalization scale between the cross sections for various vector mesons is determined mainly by the parameter A_1, and can be estimated according to the formula

$$A \sim (m_q)^{-4} M_V \Gamma_{V \to e^+e^-} (e)^2,$$

where M_V and m_q are the masses of the relevant vector mesons and the quark they contain, $\Gamma_{V \to e^+e^-}$ is the decay width of the vector meson, and e is the electric charge of the relevant quark. It reproduces qualitatively the ratio between ϕ, J/ψ and Υ photoproduction. However, since the parameter A_2 also contributes to the relative scales, we had better rely on the recently measured Υ-photoproduction cross section [32] to fit these parameters.

Setting $\gamma = 0$, we adjust uniquely the normalization constant A_1 to the measured value [32] of σ_{el} in the Υ photoproduction, and get 0.2 pb. The parameter A_2, on the other hand, shows more flexibility, varying for fixed A_1 within the range $0.1 \le A_2 \le 0.37$ pb, the central value being $A_2 = 0.2$ pb. The predicted elastic cross section is shown in Fig. 7.

Finally, we note that the present fits – because of the limited number of data points relative to the number of free parameters – should be considered as preliminary, aimed at an exploration of a dynamical mechanism of diffractive photoproduction, alternative to the existing models. Further comparison with the data may result in a different set of fitted parameters, although the general features are expected to remain unchanged.

Acknowledgements. L. Jenkovszky is grateful to the Dipartimento di Fisica dell'Universita' della Calabria, and to those at the Istituto Nazionale di Fisica Nucleare Sezione di Padova and Gruppo Collegato di Cosenza, for their warm hospitality and financial support while part of this work was done.

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