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Color evaporation and elastic Υ photoproduction at DESY HERA

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The diffractive photoproduction of vector mesons is usually described by considering the two-gluon (Pomeron) exchange, the nondiagonal parton distributions, and the contribution of the real part to the cross section. In this Brief Report we analyze the diffractive photoproduction of the Υ at DESY HERA using an alternative model, the color evaporation model (CEM), where the cross section is simply determined by the boson-gluon cross section and an assumption for the production of the colorless state. We verify that, as in the J/ψ case, the HERA data for this process can be well described by the CEM. Moreover, we propose the analysis of the ratio $R=\sigma_{\Upsilon}/\sigma_{J/\psi}$ to discriminate between the different approaches.

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The successful operation of the DESY ep collider HERA has opened a new era of experimental and theoretical investigation into diffractive vector-meson photo- and leptoproduction. On the experimental side, the HERA accelerator extends the accessible energy range by more than one order of magnitude over previous experiments. The HERA data show that the cross sections for exclusive vector-meson production rise strongly with energy when compared to fixed-target experiments, if a hard scale is present in the process. On the theoretical side, vector-meson production has proved to be a very interesting process in which to test the interplay between the perturbative and nonperturbative regimes of QCD. (For a review, see, for example, [1].) While in an inclusive process, such as open heavy flavor production, the cross section is described in terms of a perturbative term associated with the cross section of the partonic subprocess and a nonperturbative term represented by the parton distributions, an analogous factorization of hard and soft physics does not apply to quarkonium production rates [2], which constitute a small fraction of the total open flavor cross section. This makes quarkonium physics a challenging field [2].

The current picture used in the literature to describe the diffractive photo- and leptoproduction of vector mesons assumes that the color singlet property of the meson is enforced at the perturbative level by two-gluon (Pomeron) exchange [3]. In this approach the amplitude, in the target rest frame, is factorized as a sequence of events very well separated in time: (i) the photon fluctuates into a quark-antiquark pair, (ii) the $q\overline{q}$ pair scatters on the proton target, and (iii) the scattered $q\overline{q}$ pair turns into a vector meson. The interaction is mediated by the exchange of two gluons in a color singlet state. Moreover, the two-gluon exchange amplitude can be shown to be proportional to the gluon distribution $xg(x,\overline{Q}^2)$, with $x=(M^2+Q^2)/W^2$ and $\overline{Q}^2\approx\frac{1}{4}(M^2+Q^2)$, where W is the γp center of mass energy and M is the invariant mass of the $q\overline{q}$ system. In the case of the production of a heavy meson, the presence of the heavy meson mass ensures that perturbative QCD can be applied even in the photoproduction limit. This approach has been improved, particularly regarding the role of the vector-meson light cone wave function [4], and describes reasonably the HERA J/ψ data. When applied to the recent HERA Υ data [5,6], it reproduces the data only if new effects, with significant contributions are considered [7,8]: (a) the nondiagonal parton distributions, which probe new nonperturbative information about hadrons and are a generalization of the conventional parton distributions (for a review see Ref. [9]); and (b) the real part of the scattering amplitude. In Ref. [8], a strong correlation between the mass of the diffractively produced state and the energy dependence of the total cross section was found, implying a distinct energy dependence for the Υ and J/ψ photoproduction. One of the main motivations for the study of diffractive photoproduction of vector mesons in the Pomeron model is the possibility of obtaining a sensitive probe of the behavior of the gluon distribution, due to the quadratic dependence on the gluon distribution [3,10] of the cross section in this model.

An alternative view of the diffractive photoproduction process was proposed recently in Ref. [11], where the J/ψ photoproduction was analyzed using the color evaporation

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model (CEM) [12]. In this case the color singlet is not enforced at the perturbative level and the cross section for the process is given essentially by the boson-gluon cross section plus an assumption for formation of the colorless meson. In the CEM for diffractive photoproduction the cross section is linearly proportional to the gluon distribution. The authors of Ref. [11] obtained a parameter-free prediction which describes the HERA J/ψ data very well.

In this Brief Report we extend the application of the CEM to the recent HERA Υ data and verify that, using the parameters determined in Υ hadroproduction, this model reasonably describes the experimental data with no need to introduce a colorless (Pomeron) exchange at the perturbative level, or the nondiagonal parton distributions or the contribution of the real part of the scattering amplitude. Moreover, we propose the analysis of the ratio $R=\sigma_{\Upsilon}/\sigma_{J/\psi}$ to discriminate between the different approaches.

Let us start with a brief review of the color evaporation model. One of the main uncertainties in quarkonium production is related to the transition from the colored state to the colorless meson. Initially, the $q\bar{q}$ pair will in general be in a color octet state. It subsequently neutralizes its color and binds into a physical resonance. Color neutralization occurs by interaction with the surrounding color field. If we enforce the condition that a colorless object is already present at the perturbative level, then a hard interaction with the surrounding color field is assumed, and a minimum of two gluons should be exchanged with the proton (Pomeron models). However, if the colorless object is produced at the nonperturbative level, then there is no minimal restriction on the number of gluons exchanged with the proton. The CEM provides a simple and general phenomenological approach to color neutralization (see also Ref. [13]). In the CEM, quarkonium production is treated identically to open heavy quark production with the exception that in the case of quarkonium the invariant mass of the heavy quark pair is restricted to be below the open meson threshold, which is twice the mass of the lowest meson mass that can be formed with the heavy quark. For bottomonium the upper limit on the $b\bar{b}$ mass is then $2m_B$. Moreover, the CEM assumes that the quarkonium dynamics is identical to all bottomonium states, although the $b\bar{b}$ pairs are typically produced at short distances in different color, angular momentum, and spin states. The hadronization of the bottomonium states from the $b\bar{b}$ pairs is nonperturbative, usually involving the emission of one or more soft gluons. Depending on the quantum numbers of the initial $b\bar{b}$ pair and the final state bottomonium, a different matrix element is needed for the production of the bottomonium state. The averages of these nonperturbative matrix elements are combined into the universal factor $F[nJ^{PC}]$, which is process and kinematics independent and describes the probability that the $b\bar{b}$ pair binds to form a quarkonium $\Upsilon(nJ^{PC})$ of given spin J, parity P, and charge conjugation C. Once F has been fixed for each state (Υ, Υ', or Υ'') the model successfully predicts the energy and momentum dependence [14,15].

Considering the elastic Υ photoproduction at HERA, the CEM predicts that the cross section is given by

$$\sigma[\Upsilon(nJ^{PC})]=F[nJ^{PC}]\bar{\sigma}[b\bar{b}], \tag{1}$$

where the large distance factors F can be written in terms of the probability 1/9 of having a color singlet pair after the soft interactions, times the fraction ρ_i of total bottomonium carried by the different states, in a similar way as considered in [12], where the corresponding ρ factors for charmonium are claimed to be universal. The short distance contribution is

$$\bar{\sigma}[b\bar{b}]=\int_{2m_b}^{2m_B} dM_{b\bar{b}}\frac{d\sigma[b\bar{b}]}{dM_{b\bar{b}}}. \tag{2}$$

Here $\sigma[b\bar{b}]$ is the spin- and color-averaged cross section for open heavy quark production, which describes the boson-gluon fusion process $\gamma g\rightarrow b\bar{b}$; $M_{b\bar{b}}$ is the invariant mass of the $b\bar{b}$ pair, m_b is the bottom quark mass, and $2m_B$ is the $B\bar{B}$ threshold. The differential cross section for the boson-gluon subprocess is well known [see Eq. (4) in Ref. [11] for the expression at leading order (LO)]. This will contribute to elastic photoproduction, since in LO all the energy of the photon is transferred to the $b\bar{b}$ pair. Higher order corrections will be important mainly for the inclusive and inelastic cross section. Thus, the soft interactions have a double effect—to eliminate the color of the $c\bar{c}$ pair, allowing quarkonium production, and to allow elastic production with a single perturbative gluon exchange, by having soft gluon exchanges taking place in the nonperturbative part of the process.

In the CEM, the effect of these soft interactions is implicit in the nonperturbative factors. An explicit modeling for the soft gluon exchanges is done in the soft color interactions (SCI) model [13], which is based essentially on the same general idea. In that model, by requiring either rapidity gaps or leading protons in the final state, a good explicit description of several diffractive processes was obtained, including diffractive J/ψ and open beauty production in the Tevatron [16]. This shows that soft gluon exchanges really might play a role in diffraction.

The CEM has been used to predict the production of Υ in hadron and nuclear processes [15], with the parameter $F[nJ^{PC}]$ determined from the quarkonium production experimental data at fixed-target energies. A remarkable feature of the CEM is that this model also accounts (within K factors) for the quarkonium production at the Tevatron [14]. As the fixed-target Υ data have generally given the sum of Υ, Υ', and Υ'' production, because the mass resolution is too low to clearly separate the peaks, only the global factor $F[\Upsilon+\Upsilon'+\Upsilon'']=0.044$ has been determined. This is an effective value which reflects both direct production and chain decays of higher mass states. As discussed in Ref. [17], isolation of the direct production cross section for each Υ_i requires the detection of the radiated photons associated with chain decays, which is not currently available but might be possible at the CERN Large Hadron Collider (LHC). Considering some assumptions related to the decay chain the following values for F in direct Υ_i production have been estimated [17]: $F^d[\Upsilon]=0.023$, $F^d[\Upsilon']=0.02$, $F^d[\Upsilon'']=0.0074$, where the d superscript indicates the F for direct production. In our formalism the F factors can be related to

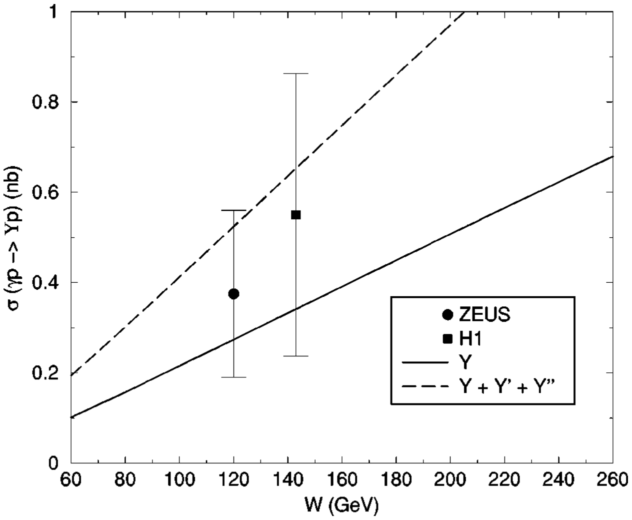

FIG. 1. Predictions of the color evaporation model for Υ photoproduction at HERA. Cross section as a function of the photon-proton center of mass energy *W*. The data points are the ZEUS and H1 Collaboration results for the direct production of the Υ state, which should be compared with the full line. The total $\Upsilon+\Upsilon'+\Upsilon''$ contribution is also shown (dashed line).

the ρ factors by the simple relation $F_i=1/9\rho_i$, where the 1/9 is the probability of having the $b\bar{b}$ pair in a color singlet state after the soft gluon exchanges, and ρ_i are the universal factors that give the fractions of the onium cross section carried by the different onium states. Their corresponding values are, from above,

$$\rho^d[\Upsilon]=0.207, \quad \rho^d[\Upsilon']=0.18, \quad \rho^d[\Upsilon'']=0.066. \tag{3}$$

Once the free parameters have been determined in the hadronic processes, we can use the CEM to predict the Υ photoproduction at HERA. This also follows the assumption used in [5] that the production ratios of Υ, Υ', and Υ'' are the same as those measured in hadron-hadron collisions. A comment is in order here. In Ref. [17] the Υ hadroproduction was calculated considering the next-to-leading order contributions for the cross section, which implies that the factor F determined from data does not contain perturbative contributions beyond leading order and can be considered a universal factor that describes the probability for quarkonium production. Moreover, the calculations in Ref. [17] used the Martin-Roberts-Stirling set $\mathrm{D}^{-'}$ (MRS $\mathrm{D}^{-'}$) parton densities as input, but, as demonstrated in [18], where an update from the analysis of the Υ suppression for the compact muon solenoid (CMS) detector was made, the Υ data can be equally well described using the 1994 Glück-Reya-Vogt (GRV 94) LO [19] parton densities.

The cross section $\bar{\sigma}[b\bar{b}]$ is computed at leading order using the GRV 94 LO [19] parton densities with $m_b=4.75$ GeV, $m_B=5.279$ GeV, and the renormalization and factorization scales set to $\mu=(M_{Q\bar{Q}})^{1/2}$ [12,11], with $Q=b$. In Fig. 1 we show our predictions for Υ photoproduction at HERA energies. Both the total $\Upsilon+\Upsilon'+\Upsilon''$ and direct Υ production are presented, since the cross sections measured by the ZEUS and H1 Collaborations did not select the direct Υ state, but rather the data were integrated over an interval of the $\mu^+\mu^-$ mass that includes at least the Υ, Υ', and Υ'' resonances. We verify that the current experimental data do not allow us to discriminate between the distinct contributions. We emphasize that our results are completely parameter-free and that the CEM reasonably describes the scarce experimental data.

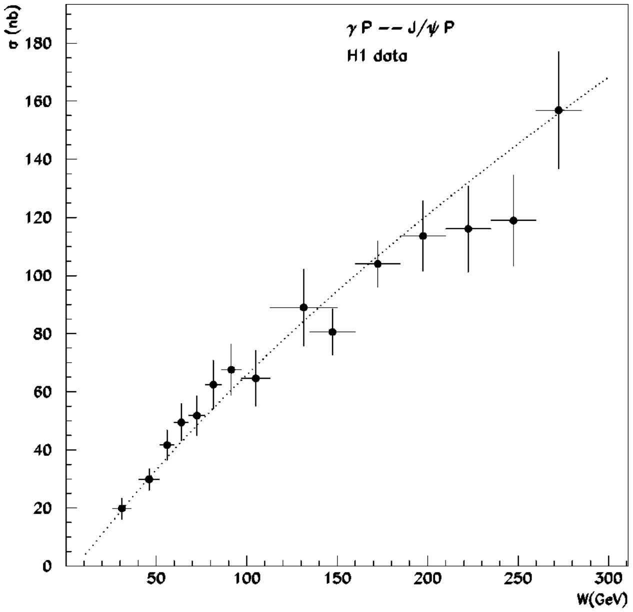

FIG. 2. Predictions of the color evaporation model for J/ψ photoproduction at HERA. Cross section as a function of the photon-proton center of mass energy *W*. The data points are the new H1 Collaboration results for J/ψ production.

The simplicity of the CEM strongly contrasts with the number of assumptions necessary in the Pomeron models to describe the same set of data. Here we propose a signature to discriminate between these models. As we quoted above, the Pomeron models predict a stronger growth in energy for the diffractive Υ photoproduction than for J/ψ photoproduction, due to the strong correlation between the mass of the diffractively produced state and the energy dependence of the cross section. In contrast, in the CEM the growth of the cross section is directly determined by the gluon distribution $xg(x,\mu)$, where μ is the factorization scale. Therefore, the energy dependence of the ratio

$$R_{\mathrm{CEM}}=\frac{\sigma_{\Upsilon}}{\sigma_{J/\psi}} \tag{4}$$

can be used to discriminate between the models.

As an intermediate step to calculate the rate mentioned, we show in Fig. 2 our previous calculation of $\sigma_{J/\psi}$, contrasted with the more recent HERA data [6]. We see that these data can be reasonable explained without tuning the parameters, which were taken as those previously used in Ref. [11]. This gives one more clue that the CEM can be used to explain elastic J/ψ photoproduction.

In Fig. 3 we present the energy dependence of the ratio $R_{\mathrm{CEM}}=\sigma_{\Upsilon}/\sigma_{J/\psi}$ calculated using the CEM, where σ_{Υ} repre-

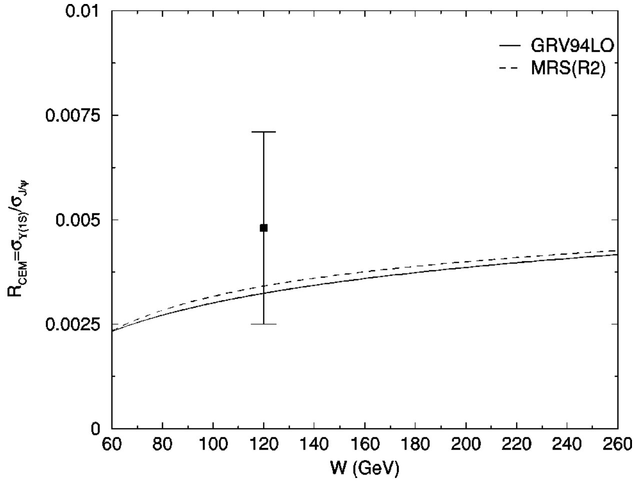

FIG. 3. Predictions of the color evaporation model for the energy dependence of the ratio $R_{\rm CEM}=\sigma_{\Upsilon}/\sigma_{J/\psi}$ in photoproduction at HERA. Data from ZEUS Collaboration.

sents the direct Υ production and we have used the results from Ref. [11] and from above to calculate $\sigma_{J/\psi}$. Our results show that this ratio is almost constant in the kinematic range of HERA, in contrast to the Pomeron model [8], where a steep rise of the ratio is predicted (cf. Ref. [8], $R_{\rm Pom}\propto W$). This ratio was also obtained in [7], where the value predicted agrees with data within errors for the MRS gluon, but underestimates the result for the steeper GRV gluon. In our case, the $\sigma_{\Upsilon}/\sigma_{J/\psi}$ ratio agrees with the lower bound observed by the ZEUS Collaboration [5] for both MRS and GRV gluon parametrizations.

The original motivation for the study of diffractive photoproduction was the possibility of extracting the gluon distribution inside the proton. However, the dependence on the gluon distribution is one of the major differences between the descriptions of the diffractive photoproduction using the Pomeron model and the CEM. Whereas the Pomeron model has a quadratic dependence on xg, this dependence is linear in the CEM. Our result demonstrates that, before extracting the gluon distribution from HERA Υ and J/ψ data, one should determine the correct description for this process, for example, by measuring the energy behavior of the $\sigma_{\Upsilon}/\sigma_{J/\psi}$ ratio.

The CEM describes a large range of data in hadro- and photoproduction, as shown in Refs. [12,11,20]. Using this model, in this Brief Report we obtain a parameter-free description of the elastic Υ photoproduction at HERA energies. We verify that this simple model reasonably describes the experimental data, similarly to the Pomeron models. As a distinct feature between these models, the CEM predicts a softer energy dependence of the ratio between the Υ and J/ψ cross sections. Of course, when more precise data become available, discrimination between these models should be possible, which will allow us to decide whether the CEM is only an alternative phenomenological model for the current energies or whether it contains some underlying nonperturbative dynamics that is important in both diffractive and nondiffractive quarkonium production. In the latter case, more theoretical studies will be necessary to understand the soft interactions in the process of color neutralization.

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