Photoproduction of Heavy Quarkonia

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Abstract. We investigate the reaction $\gamma p \to V p$, with $V$ denoting a $\Phi$ or a $J/\Psi$ meson, within the scope of perturbative QCD, treating the proton as a quark-diquark system. Our predictions extrapolate the existing forward differential cross-section data into the few-GeV momentum-transfer region. In case of the $J/\Psi$ reasonable results are only obtained by properly taking into account its mass in the perturbative calculation of the hard-scattering amplitude.

INTRODUCTION

Within the last few years exclusive photoproduction of vector mesons ($\rho, \omega, \Phi, J/\Psi$) has attained increasing interest which has been stimulated by corresponding experimental efforts at DESY and TJLab. The investigation of high-energy diffractive photoproduction at DESY aims at a better understanding of Pomeron phenomenology in terms of QCD. The 93-031 experiment at TJLab, on the other hand, is situated in the few-GeV (momentum-transfer) region and tries to shed some light on the transition from the non-perturbative (vector-meson dominance) to the perturbative (quark and gluon exchange) production mechanism. For heavy-quarkonium channels the perturbative production mechanism becomes particularly simple. Whereas $\rho$ and $\omega$ production can proceed via both, quark and gluon exchange, heavy quarkonia are produced via gluon exchange mainly. Quark exchange is power-suppressed due to the small heavy-quark content of the nucleon.

In the present contribution we report on an attempt to describe photoproduction of $\Phi$ and $J/\Psi$ mesons in the perturbative regime by means of a modified version of the hard-scattering approach (HSA), in which the proton is treated as a quark-diquark rather than a three-quark system. This perturbative diquark model accounts effectively for quark-quark correlations inside a baryon and has already successfully been applied to the investigation of various exclusive photon-induced reactions [1, 2, 3, 4, 5, 6]. It provides a consistent description of baryon electromagnetic form factors, Compton scattering off baryons, photoproduction of $K$ mesons, etc., in the range of intermediate momentum transfers ($p_{\perp}^2 \gtrsim 3$ GeV$^2$) in the sense that data for these reactions are reproduced with the same set of model parameters.

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THE HARD-SCATTERING APPROACH WITH DIQUARKS

Within the HSA an exclusive scattering amplitude $M$ can be written as a convolution integral of a perturbatively calculable hard-scattering amplitude $T_{\{\lambda\}}$ with distribution amplitudes $\phi_H$, which contain the bound state dynamics of the involved hadrons $H$. For the photoproduction reaction $\gamma p \rightarrow V p$ this integral takes on the particular form

$$M_{\{\lambda\}}(\tilde{s}, \tilde{t}) = \int_0^1 dx_1 dy_1 dz_1 \phi_V^\dagger(z_1) \phi_p^\dagger(y_1) T_{\{\lambda\}}(x_1, y_1, z_1; \tilde{s}, \tilde{t}) \phi_p(x_1). \quad (1)$$

The distribution amplitudes $\phi_H$ are probability amplitudes for finding the valence-Fock state in the hadron $H$ with its constituents carrying certain fractions $x_i, y_i, z_i, i = 1, 2$ of the momentum of their parent hadron. In the diquark approach the valence-Fock state of a baryon is assumed to consist of a quark ($q$) and a diquark ($D$). The hard-scattering amplitude $T_{\{\lambda\}}$ is calculated on tree level in collinear approximation. The subscript $\{\lambda\}$ of $T$ and $M$ represents a set of possible photon, proton, and vector-meson helicities. The analytical results are conveniently expressed in terms of Mandelstam variables $\tilde{s}, \tilde{t},$ and $\tilde{u}$, which are obtained by neglecting the proton mass. All hadron masses, however, are fully taken into account in flux and phase-space factors.

The model, as applied in Refs. [1, 2, 3, 4, 6] includes scalar as well as axial-vector diquarks. Feynman rules, the quark-diquark distribution amplitude of the proton, and further details of the diquark model can be found in Ref. [1]. The numerical values of the model parameters for the present work are also adopted from that paper. In order to describe $\Phi$- and $J/\Psi$-meson photoproduction simultaneously we have modified the $\Phi$-meson distribution amplitude proposed by Benayoun and Chernyak [7] by attaching a flavor dependent exponential factor (cf. Ref. [6]).

Unlike the pure HSA, in which hadron masses are completely neglected in the calculation of the hard-scattering amplitude, we include them in our calculation. This improves the applicability of the model at momentum transfers of only a few GeV, where mass effects may still be important. Our treatment of mass effects parallels the one described in detail in Ref. [6]. In that work an expansion in powers of $(m_H/\sqrt{s})$ at fixed scattering angle has been performed. Only leading order and next-to-leading order terms in the expansion have been kept. Whereas this procedure gives a reasonable description of photoproduction of $\Phi$ mesons in the few-GeV momentum-transfer range, it fails in the case of the heavier $J/\Psi$ mesons. Therefore we take the $J/\Psi$ mass fully into account, treat the proton-mass, however, still like in Ref. [6].

RESULTS AND CONCLUSIONS

Photoproduction of $\Phi$ mesons in the forward-scattering domain can be well described by simple Pomeron phenomenology [8]. At higher momentum transfers a QCD-inspired version of the Pomeron-exchange model has been proposed by Laget and Mendez-Galain [9], in which the Pomeron is replaced by two (Abelian) gluons. If only those graphs are taken into account in which the two gluons couple to the same quark in the proton, the two-gluon cross section exhibits a characteristic node due to an interference
FIGURE 1. Differential cross section for $\gamma p \rightarrow J/\Psi p$ versus momentum transfer $-t$ at photon laboratory energies of 150 GeV (left) and 4708 GeV (right). Data are taken from Binkley et al. [12] and Breitweg et al. [13], respectively. Diquark model predictions are shown for different treatments of the $J/\Psi$ mass: full inclusion of the $J/\Psi$ mass (solid), leading (dashed), and next-to-leading order (dash-dotted) of an expansion in $(M_{J/\Psi}/\sqrt{s})$.

of the two different Feynman diagrams contributing to the photoproduction amplitude. By additionally considering diagrams, in which the gluons couple to different quarks in the proton this node is completely washed out [10]. For $|t| \gtrsim 4$ GeV$^2$ the resulting differential cross section becomes then comparable with the diquark-model prediction [6]. This similarity is not surprising since it is known that the hard-scattering mechanism, i.e. diagrams without loops, in which all hadronic constituents are connected via gluon exchange, becomes dominant in the kinematic range of large $t$ and $u$.

Difficulties arise if $J/\Psi$ production is considered. Both, Pomeron exchange as well as two-gluon exchange overestimate the differential cross section by at least one order of magnitude. The results are improved by arguing that the coupling of the Pomeron (or the two gluons) to a charmed quark is weaker than to a strange quark. If hadron masses are treated like in Ref. [6] similar difficulties are encountered within the diquark model. With the modified treatment of mass effects in which the meson mass is fully taken into account (for details see, e.g., Ref. [11]), this deficiency is, however, cured.

Figure 1 shows the diquark-model predictions for $d\sigma/dt$ at photon energies of 150 GeV and 4708 GeV, respectively, together with experimental data from FNAL [12] and DESY [13]. Due to the lack of data in the region of large transverse momentum transfers (i.e. large $t$ and $u$) a direct comparison of our predictions with experiment is not possible, since the perturbatively inspired diquark model is not expected to be applicable in the kinematic region of $p_{\perp}^2 \lesssim 3$ GeV$^2$. The diquark-model predictions with the $J/\Psi$ mass fully included, however, extrapolate the low-$t$ data in a reasonable way. By comparing the leading and next-to-leading-order results of the expansion in $(M_{J/\Psi}/\sqrt{s})$ it becomes obvious that such a series expansion converges rather poorly.
A closer inspection reveals that the expansion coefficients are angular dependent. The leading-order terms are only dominant for sufficiently large deflections. Towards smaller scattering angles mass-correction terms become increasingly important. For FNAL and HERA energies momentum transfers of a few GeV just mean that we deal with nearly forward scattering and thus we should refrain from an expansion in the $J/\Psi$ mass.

As one would expect, the effect of taking the meson mass fully into account is much less pronounced in $\Phi$ production than in $J/\Psi$ production. For equal values of the mass-expansion parameter $(M_{V}/\sqrt{s})$ and of Mandelstam $t$ the photon laboratory energy for $\Phi$ production has to be smaller by about a factor $(M_{\Phi}/M_{J/\Psi})^2 = 0.11$ and correspondingly the scattering angle has to be larger, so that the leading-order terms in the mass expansion become dominant. But also in $\Phi$ production the full inclusion of the $\Phi$ mass has a positive effect. It slightly improves the angular dependence of the differential cross-section as compared to the approximate mass treatment of Ref. [6]. A full account of diquark-model predictions for $\Phi$ and $J/\Psi$ photoproduction, which includes also spin observables, can be found in Ref. [11].

To sort out whether perturbative photoproduction mechanisms already start to dominate in the few-GeV momentum-transfer region precision data for $|t| \gtrsim 3$ GeV$^2$ are doubtlessly needed. A severe test for a perturbative model, like the diquark model, would, however, be its confrontation with data for polarization observables. Hard scattering is closely connected with hadronic helicity conservation. Polarization observables could help to reveal whether the inclusion of constituent-masses and two-quark correlations in terms of diquarks suffices to model higher-twist and non-perturbative effects, or whether other (non-perturbative) mechanisms have to be considered.

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REFERENCES

1. Jakob, R., Kroll, P., Schürmann, M., and Schweiger, W., Z. Phys., A347, 109-116 (1993).
2. Kroll, P., Pilsmner, Th., Schürmann, M., and Schweiger, W., Phys. Lett., B316, 546-554 (1993).
3. Kroll, P., Schürmann, M., and Guichon, P.A.M., Nucl. Phys., A598, 435-583 (1996).
4. Berger, C.F., Exclusive Two-Photon Reactions in the Few-GeV Region, diploma thesis, Technological University of Graz, Graz (1997).
5. Kroll, P., Schürmann, M., Passek, K., and Schweiger, W., Phys. Rev., D55, 4315-4328 (1997).
6. Berger, C.F., and Schweiger, W., Phys. Rev., D61, 114026 (2000).
7. Benayoun, M., and Chernyak, V.L., Nucl. Phys., B329, 285-313 (1990).
8. Donnachie, A., and Landshoff, P.V., Nucl. Phys., B311, 509-521 (1989).
9. Laget, J.-M., and Mendez-Galain, R., Nucl. Phys., A581, 397-428 (1995).
10. Laget, J.-M., Phys. Lett., B489, 313-318 (2000).
11. Jäger, B., Photoproduction of Heavy Quarkonia, diploma thesis, Karl-Franzens University of Graz, Graz (2001).
12. Binkley, M. et al., Phys. Rev. Lett., 48, 73-76 (1982).
13. Breitweg, J. et al., Eur. Phys. J., C14, 213-238 (2000).