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DIFFRACTIVE PHOTOPRODUCTION OF VECTOR MESONS AT LARGE MOMENTUM TRANSFER

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Diffractive photoproduction of ρ, ϕ and J/ψ was studied in the BFKL approach to hard colour singlet exchange. Differential cross sections, the energy dependence and spin density matrix elements were calculated and compared to data from HERA. The overall description of data is reasonably good, except of the single flip amplitude which has the wrong sign. Importance of chiral odd components of the photon is stressed.

1 Introduction

Diffractive photoproduction of vector mesons (VM) off a proton target at large momentum transfer is a process observed at HERA at rather high rates [1,2]. In this process the proton, typically, dissociates forming a diffractive system and vector mesons are observed via their decay channels. The recorded statistics is quite high for ρ, ϕ and J/ψ production up to momentum transfer of $|t| \sim 20$ GeV^2. The most interesting observables that are measured are the differential cross-section $d\sigma/dt$, its dependence on the γp collision energy W and the spin density matrix elements r_{ij}^{04}. The determination of the latter is possible from the angular distribution of the decay products of the mesons. The spin density matrix elements are governed by the photoproduction amplitudes of a polarised vector meson by a polarised quasi-real photon.

It follows from a phenomenological rule of the s-channel helicity conservation (SCHC) that the meson should have the same polarisation as the incoming photon. Indeed, this option dominates but the data for ρ and ϕ exhibit some deviations from the SCHC scenario. It was determined that the the amplitude with a single helicity flip M_{+0} (that is a photon with helicity $+1$ going into longitudinally polarised meson) and double helicity flip, M_{+-}, measure about 10% and 20% of the leading, helicity conserving amplitude, M_{++}, respectively. Thus, the simplest scheme of SCHC is not sufficient and it is worth performing a QCD analysis of the process. The requirement of obtaining a good simultaneous description of the shapes and magnitudes of cross sections and the spin density matrix elements is rather stringent and discriminates between various QCD-based models.

In perturbative QCD vector meson photoproduction at high energies is mediated by an exchange of a gluonic system in a colour singlet state. In the leading order approximation the system is just two elementary, non-interacting gluons. A detailed calculation [3] for light vector mesons based on this assumption implied that the single flip amplitude should be leading at sufficiently large momentum transfer, and the total cross section should have an approximate power-like behaviour, $d\sigma/dt \sim 1/|t|^3$. The shape of the cross section agrees with the data, but the prediction about the leading amplitude is not correct. Even worse, according to the model the actually leading M_{++} amplitude would give $d\sigma/dt \sim 1/|t|^4$. In search of the source of the discrepancy, an important idea was put forward [3] that a non-perturbative component of the photon wave function, related to chiral odd quark operators, makes important contribution to the production amplitudes. In a perturbative approach, the current light quark mass is used, which is negligibly small and may be set to zero (this is the reason that the M_{++} amplitude is naively expected to be suppressed in the light meson case). The QCD vacuum, however, is a medium which breaks the chiral symmetry, the phenomenon responsible, for instance, for the generation of the constituent mass of quarks. Indeed, the chiral odd no-flip amplitude, M^{odd}_{++}, was found to be the largest one at a moderate momentum transfer $|t| < 20$ GeV^2. Still, a good quantitative description of the bulk of data was not reached.

On the other hand, the helicity averaged differential cross sections for the VM photoproduction are well described by the leading logarithmic BFKL formalism with non-relativistic wave functions, both for J/ψ and for the light vector mesons [4]. Remarkably, in the non-relativistic picture the whole contribution to the cross section is given by the chiral odd no-flip amplitude and the constituent quark masses naturally enter the calculation. A main drawback of this approach is an inability to describe deviations from the SCHC and in order to improve it one needs to go beyond the non-relativistic approximation. Thus, the main goal of our analysis [5,6,7] was to employ the non-forward BFKL equation [8] to describe the hard colour singlet exchange and combine it with a QCD guided description of the meson wave functions.

2 Formalism

The BFKL equation in the leading logarithmic approximation describes the evolution of the diffractive scattering amplitude with the rising rapidity distance Y between the colliding objects. Perturbative QCD corrections to the simple two gluon exchange have leading pieces $\sim (\alpha_s Y)^n$, and in spite of α_s being small, the higher order terms cannot be neglected. Thus, the BFKL equation resums ladder diagrams, with reggeised gluons along the ladder. The equation is an integral equation in the transverse momentum of the gluons. The integral kernel exhibits the global conformal invariance, when expressed in the complex representation of gluon transverse positions, and due to that symmetry the Eigenfunctions of the BFKL integral kernel $E_{n,\nu}$ may be found analytically. In this representation, the BFKL amplitude may be written in a compact form, for any momentum transfer $\vec{q}$ as an infinite sum over all conformal spins n,

$$M(\vec{q},Y) = \sum_{n=-\infty}^{\infty} \int d\nu \, \frac{(\nu^2+n^2/4)\exp[\alpha_s Y \chi_n(\nu)]}{[\nu^2+(n-1)^2/4)^2][\nu^2+(n+1)^2/4]} \, (E_{n,\nu}|\Phi_1)(\Phi_2|E_{n,\nu}) \tag{1}$$

The Eigenvalues of the BFKL kernel $\chi_n(\nu) = 4\mathrm{Re}\,[\psi(1) - \psi(1/2 + |n|/2 + i\nu)]$ govern the dependence on the rapidity, and for $Y \gg 1$ the conformal spin $n = 0$ yields the leading contribution, giving the amplitude which grows with rapidity, $M \sim \exp(12 Y \alpha_s \ln 2/\pi)$. Impact factors Φ_i are amplitudes for transition of the projectile and the target into their final states, e.g. a $\gamma \to V$ and $p \to X$ transitions in the VM photoproduction. The impact factors in Eq. 1 have been, symbolically, projected on the the BFKL Eigenfunctions.

The helicity dependent impact factors, $\Phi(\gamma \to V)$, may be calculated in perturbative QCD under some assumptions about the wave functions of the polarised vector meson and of the polarised photon. The hard colour singlet exchange is a short distance process, thus the short distance expansion for the vector meson wave function is a natural starting point. Following [9,10,3] we used QCD distribution amplitudes up to twist 3, taking into account both chiral even and chiral odd ones. We chose to use the perturbative expression for the photon wave function, with a constituent quark mass m_q. The mass is an effective parameter here and it plays a dual rôle: it sets the magnitude of the chiral odd pieces and it provides an infrared cutoff for the size of hadronic system that the photon fluctuates into. In both cases, the actual constituent light quark mass $m_q \simeq 0.3 - 0.4$ GeV is a sensible choice. Sensitivity of the amplitudes to the value of the infrared cutoff gives an estimate the validity of the short distance expansion.

We treated the impact factor describing the diffractive proton dissociation in the standard way. At large momentum transfer the BFKL pomeron couples predominantly to individual partons in an incoherent way. Therefore the cross section may be factorised into partonic cross sections and partonic densities. The issue of how to define the BFKL impact factor for a colourful object was studied before [11,12].

3 Results

The essential parameters of our analysis were the strong coupling constant that scales the overall normalisation (α_s^{IF}), the strong coupling constant that governs the BFKL rapidity dependence (α_s^{BFKL}) and the value of constituent quark mass. The different values of α_s^{IF} and α_s^{BFKL} reflect the fact that non-leading QCD corrections to the BFKL intercept and to the impact factors may be very different. For reference, we chose to set the constituent quark mass to a half of the meson mass. We included contribution to the scattering amplitudes from all the conformal spins. The parton level BFKL amplitudes were convoluted with the parton densities, respecting the experimental cuts.

We determined the BFKL evolution of all the independent helicity amplitudes for ρ, ϕ and J/ψ photoproduction. All end-point infra-red divergencies which were

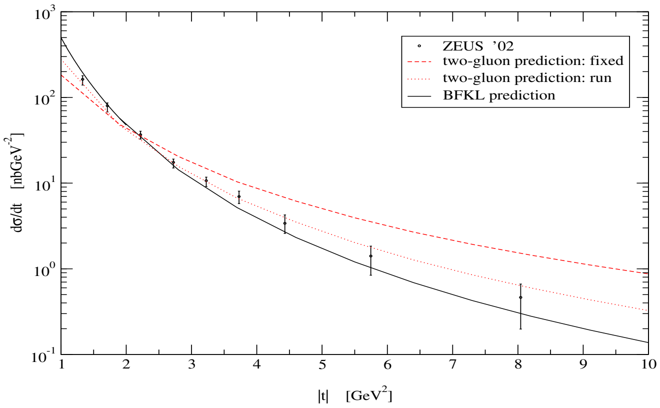

Figure 1. $d\sigma/dt$ for diffractive ρ photoproduction: ZEUS data and theory prediction in the two gluon approximation with fixed α_s (dashed line), running α_s (dotted line) and the BFKL results (continuous line).

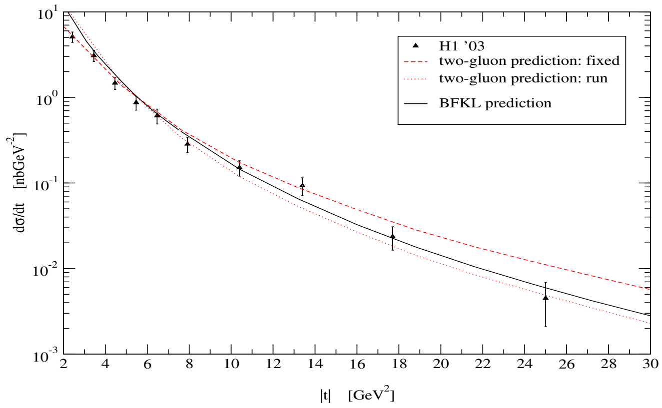

Figure 2. $d\sigma/dt$ for diffractive J/ψ photoproduction: H1 data and theory prediction in the two gluon approximation with fixed α_s (dashed line), running α_s (dotted line) and the BFKL results (continuous line).

found in the two-gluon approximations disappear for rapidities $Y > 0$ which justifies the perturbative approach. We observed that the BFKL enhancement of the chiral odd no-flip amplitude M_{++} is the strongest, and that this part of the amplitude gives the dominant contribution to the cross section. The relative significance of the single flip amplitude turned out to be much smaller than it was in the two-gluon exchange approximation, see Fig. 3.

Cross sections. The hadronic level cross sections were calculated using partonic cross sections for all possible polarisations of the photon and of the meson. For light vector mesons the shape of differential cross section is well reproduced by the BFKL curve (see Fig. 1), the two-gluon exchange approximation gives an equally good fit for the running α_s and does somewhat worse for the fixed coupling. Hence, after inclusion of the chiral odd component of the photon, the dominance of the no-flip amplitude was found not to contradict the $\sim |t|^{-3}$ dependence of $d\sigma/dt$. The results look rather similar for the ϕ photoproduction. In the J/ψ case (see Fig. 2), we found that a good fit of $d\sigma/dt$ may be obtained both in the BFKL approach and in the two gluon approximation if the QCD distribution amplitudes are used to describe the J/ψ wave function [6,7]. The t-shape is stable against the treatment of the higher order QCD corrections also when the non-relativistic approximation is employed [4,5].

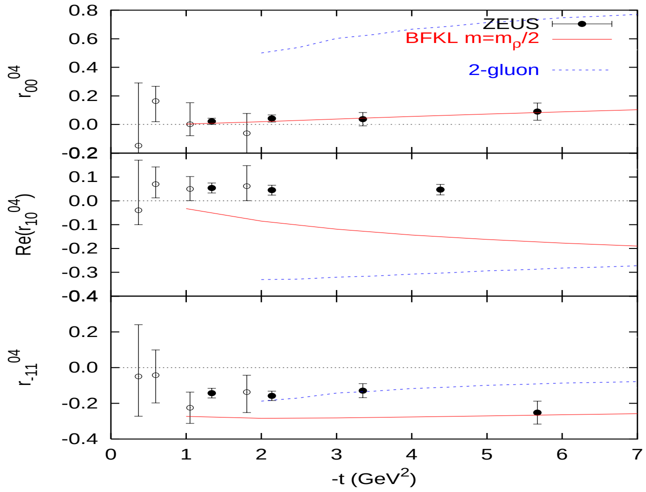

Figure 3. Spin density matrix elements: ZEUS data compared with the results of the BFKL calculation, and the two-gluon exchange approximation as functions of the momentum transfer.

Spin density matrix. The angular dependence of the photoproduced vector meson decay products is characterised by three elements of the spin density matrix: $r^{04}_{00} \sim |M_{+0}|^2$, $r^{04}_{10} \sim \mathrm{Re}\,[M^*_{+0}(M_{++} - M_{+-})]$ and $r^{04}_{1-1} \sim \mathrm{Re}\,[(M_{++}M^*_{+-})]$. In Fig. 3 we show the spin density matrix data compared with the results of the BFKL calculation [6,7]. It is clear, that r^{04}_{00} comes out right, r^{04}_{10} has the wrong sign and r^{04}_{1-1} is too negative. This means that the sign of the single flip amplitude is the most serious problem. Let us add, that when the physics constraints on m_q are relaxed and m_q is set to 1 GeV, a good fit of the ρ and ϕ data is obtained. Of course, this is only a hint that perhaps we neglected in our analysis a mechanism that cuts off larger dipoles, e.g. vector meson size or saturation effects. Data for J/ψ have rather large errors and they are consistent with zero. They are well described in the both approaches to the meson wave function. If the data improved, though, the appearance of deviations from SCHC would indicate that one should go beyond the non-relativistic approximation also in the J/ψ case.

Energy dependence. Measurements of $d\sigma/dt$ for J/ψ photoproduction at γp energy 100 GeV and 200 GeV provide some information on the value of the pomeron intercept. We used both LL BFKL (with intercept $\alpha_P \simeq 1.45$) and a BFKL formalism modified phenomenologically to incorporate non-leading corrections $\alpha_P \simeq 1.3$. The data show some growth with the energy which, within errors, is consistent with both results, with slight preference for the lower intercept.

4 Conclusions

Inclusion of BFKL evolution into a description of diffractive vector meson photoproduction substantially improves the understanding of data. Having very few free parameters, we get good fits to differential cross sections, the correct hierarchy of helicity dependent amplitudes for ρ, ϕ and J/ψ and the correct energy dependence for J/ψ photoproduction. Only the sign of the single flip amplitude comes out incorrect. This observable turns out, however, to be most sensitive to contributions from colour dipoles of moderate size. Moreover, we confirmed that the chiral odd components of the photon have to be taken into account in order to describe properly the light vector meson photoproduction.

References

1. S. Chekanov *et al.* [ZEUS Collaboration], *Eur. Phys. J.* **C26** (2003) 389.
2. A. Aktas *et al.* [H1 Collaboration], Phys. Lett. B **568** (2003) 205
3. D. Y. Ivanov, R. Kirschner, A. Schäfer and L. Szymanowski, *Phys. Lett.* **B478** (2000) 101 [Erratum-*ibid.* **B498** (2001) 295].
4. J. R. Forshaw and G. Poludniowski, *Eur. Phys. J.* **C26** (2003) 411.
5. R. Enberg, L. Motyka and G. Poludniowski, *Eur. Phys. J.* **C26** (2002) 219.
6. R. Enberg, J. R. Forshaw, L. Motyka and G. Poludniowski, *JHEP* **0309** (2003) 008.
7. G. G. Poludniowski, R. Enberg, J. R. Forshaw and L. Motyka, *JHEP* **0312** (2003) 002.
8. L. N. Lipatov, *Sov. J. Nucl. Phys.* **23** (1976) 338; E. A. Kuraev, L. N. Lipatov and V. S. Fadin, *Sov. Phys. JETP* **44**, 443 (1976); *ibid.* **45** (1977) 199; I. I. Balitsky and L. N. Lipatov, *Sov. J. Nucl. Phys.* **28** (1978) 822. L. N. Lipatov, Sov. Phys. JETP **63** (1986) 904; *Phys. Rep.* **286** (1997) 131.
9. P. Ball, V. M. Braun, Y. Koike and K. Tanaka, *Nucl. Phys.* **B529** (1998) 323.
10. P. Ball and V. M. Braun, *Nucl. Phys.* **B543** (1999) 201.
11. A. H. Mueller and W.-K. Tang, *Phys. Lett.* **B284** (1992) 123.
12. L. Motyka, A. D. Martin and M. G. Ryskin, *Phys. Lett.* **B524** (2002) 107.