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Vector Meson Production at Large Q^2 and $|t|$ at HERA

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Abstract: New results on exclusive vector meson (VM) production are presented. The data extend the previously explored phase space towards large values of the 4-momentum transfer squared $|t|$ at the proton vertex. In combination with earlier VM results the behaviour as a function of the scales $|t|$, Q^2 and M_V^2 is studied. Comparisons with calculations in the framework of perturbative QCD are shown. First measurements of the $\gamma \to \rho^0$ and ϕ helicity state transitions at large values of $|t|$ are also reported.

1. Introduction

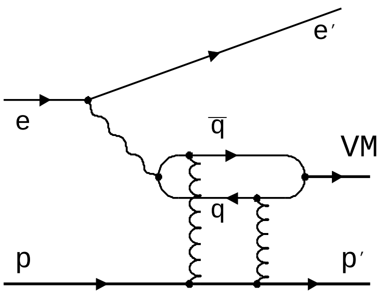

Figure 1: Diffractive vector meson production in *ep* scattering.

Diffractive VM production can be measured in the HERA *ep* collider experiments, H1 and ZEUS, over a wide kinematic range of several variables. These include the negative 4-momentum transfer squared, virtuality, of the photon Q^2, the 4-momentum transfer squared $-t$ at the proton vertex and the energy $W_{\gamma p}$ of the photon-proton centre-of-mass system.

In perturbative QCD (pQCD), in lowest order, the process of diffractive vector meson production in *ep* scattering (see fig. 1) is viewed as a sequence of several processes separated in time: an almost real or virtual photon is emitted from the incoming lepton and, long before the hard interaction, fluctuates into a $q\bar{q}$ pair. The $q\bar{q}$ pair subsequently interacts with the proton via the exchange of two (or more) gluons in a colour-singlet state and much later evolves into a real vector meson.

At small $|t|$ the elastic process in which the proton stays intact dominates. At large values of $|t|$ the dissociation of the proton into a small invariant mass state becomes dominant. Measurements are available for ρ^0, ω, ϕ, J/ψ, ψ' and Υ production spanning the ranges of $0 \simeq Q^2 < 100$ GeV^2, $0 \simeq |t| < 20$ GeV^2 and $20 < W_{\gamma p} < 290$ GeV. Perturbative calculations in QCD are available for the kinematic regions in which at least one of the energy scales μ^2, i.e. Q^2, M_V^2 or $|t|$, is large and the strong coupling constant $\alpha_s(\mu^2)$ is

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small. In the presence of such a 'hard' scale, QCD predicts a steep rise of the cross section with $W_{\gamma p}$. At large values of $|t|$, the $|t|$-dependence is expected to follow $|t|^{-n}$ [1]. At small values of Q^2, M_V and $|t|$, VM production is known to show a non-perturbative 'soft' behaviour described e.g. by Regge-type ansatzes (see also [2]).

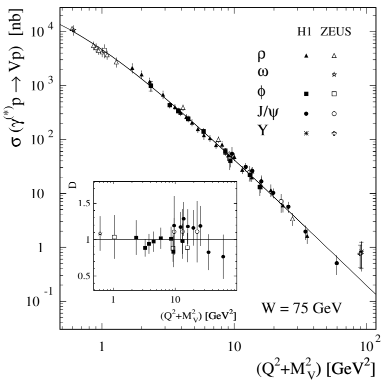

Figure 2: The total VM cross sections $\sigma(\gamma^* p \to Vp)$ scaled by SU(4) factors as a function of $Q^2 + M_V^2$ [3].

In pQCD, for Q^2 much larger than the mass squared of the vector meson, M_V^2, flavour independence, often called 'VM universality' is expected. This means that at large values of Q^2 and/or M_V^2, taking the charges of the VM constituent quarks into account ('SU(4) factors'), the VM cross sections should be approximately equal. This approximate universality is shown in fig.2 for the elastic VM production cross sections as a function of $Q^2 + M_V^2$ at constant $W_{\gamma p}$. However, universality is not expected to hold exactly, and indeed, recently, more precise data show that the ratio $J/\psi/\rho^0$ is larger than naively expected [2].

Experimentally, the various scale variables Q^2, M_V^2 and $|t|$ can be simultaneously and independently controlled. VM production is thus a very suitable testing ground for the quantitative understanding of the transition between hard and soft behaviour and the interplay between the different scale variables. Recently, new data at large values of $|t|$ have become available and thus allow tests of the applicability of the scale variable t for pQCD calculations.

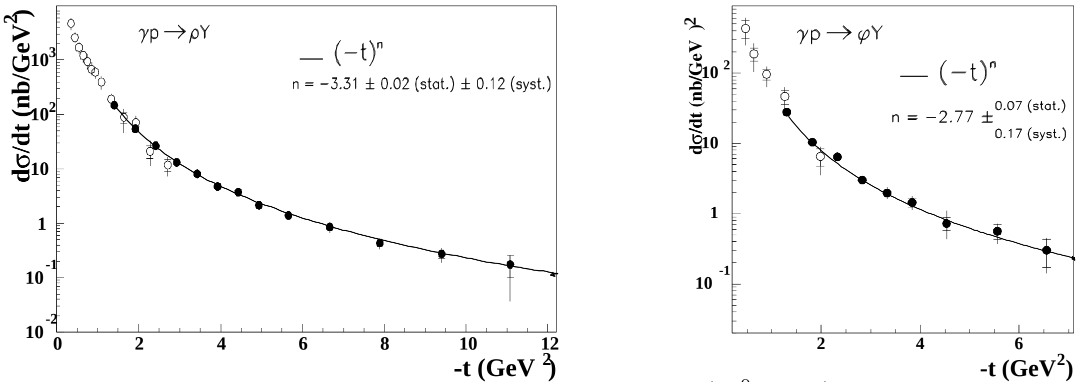

Figure 3: The differential photoproduction cross section for a) ρ^0 and b) ϕ production as a function of $|t|$ from ZEUS (bullets). The open points show an earlier measurement by ZEUS [10].

2. VM photoproduction at high $|t|$

Photoproduction ($Q^2 \sim 0$) of ρ^0 and ϕ mesons with proton dissociation have been measured by the ZEUS collaboration [4] up to values of $|t| < 11$ GeV^2 and $|t| < 7$ GeV^2, respectively (fig. 3). For $|t| \gtrsim 1$ GeV^2, the data reveal a power law behaviour which may be parametrized as $|t|^{-n}$, with $n \simeq 3$. Figure 4a) shows results on proton dissociative J/ψ photoproduction obtained by the ZEUS collaboration [4] together with a leading order calculation [5] based on BFKL evolution. The band shows the variation when changing the LO coupling constant $\bar{\alpha}_s$ and the energy scale W_0 by 10%. Compared to the light vector mesons, the $|t|$-dependence is even flatter ($|t|^{-n}$ with $n \simeq 1.7$). A new measurement of this process by the H1 collaboration [6] extends the $|t|$-range up to 21 GeV^2 (see fig. 4b). The curve shows the prediction by [5] which describes the data reasonably well over the full $|t|$-range.

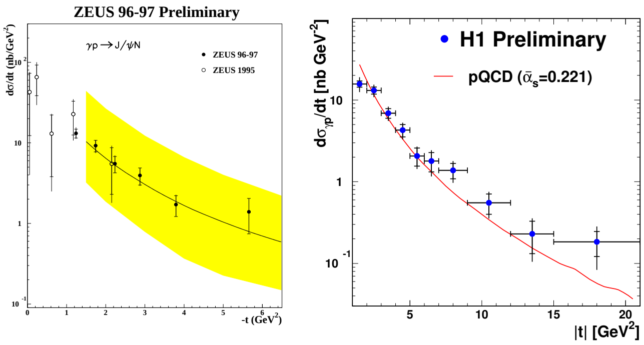

Figure 4: The differential J/ψ photoproduction proton dissociation cross section $d\sigma/dt$ as a function of $|t|$ from a) ZEUS b) H1. The curves show the predictions by [5].

The roles played by the variables $|t|$ and Q^2 are compared in fig. 5. Cross section ratios $\sigma_\phi/\sigma_{\rho^0}$ and $\sigma_{J/\psi}/\sigma_{\rho^0}$ are shown as a function of Q^2 or $|t|$. The Q^2-dependence (open points) is obtained from elastic data at low $|t|$. An increase with Q^2 is revealed. While the ratio $\sigma_\phi/\sigma_{\rho^0}$ (fig. 5a) reaches the value expected from SU(4), 2/9, the ratio $\sigma_{J/\psi}/\sigma_{\rho^0}$ (fig. 5b) is significantly lower than the naive expectation of 8/9 even at high Q^2. The proton dissociation data (full points), plotted as a function of $|t|$ in the same figures, also rise steeply with $|t|$, indicating that $|t|$ is indeed a 'hard' scale. However, quantitatively the behaviour with $|t|$ is somewhat different than that with Q^2.

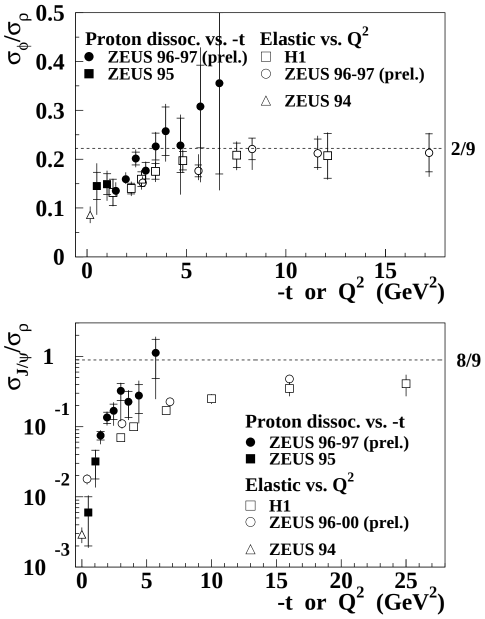

Figure 5: The ratios a) $\sigma_\phi/\sigma_{\rho^0}$ and b) $\sigma_{J/\psi}/\sigma_{\rho^0}$. The open (full) points depict the data as a function of Q^2 ($|t|$) for elastic (proton dissociative) events respectively.

3. Helicity Studies

The transitions between different helicity states from the photon to the vector meson can be studied by measuring the distributions of the production and decay angles: Φ, the angle between the lepton scattering plane and the VM production plane; ϕ, the angle between the VM production plane and the meson decay plane; and θ, the angle between the ρ^0 meson direction and the positively charged decay-π in the ρ^0 meson rest frame. The angular distributions give access to the 15 combinations of spin density matrix elements[1] $r_{ij}^{\alpha\beta}$ which in turn are products of the helicity transition amplitudes $T_{\lambda_{VM}\lambda_\gamma}$. In the case of s-channel helicity conservation, no transitions, e.g. from a transversely polarized photon into a longitudinally polarized vector meson are expected, i.e. $T_{ij} = 0$ for $i \neq j$. Previous measurements [3, 8]

[1]Here the convention of [7] is used.

have shown that s-channel helicity is not generally conserved in vector meson production. In particular, the spin density matrix element r^5_{00} has been measured to be non-zero. So far the data has been successfully described by a model using pQCD [11].

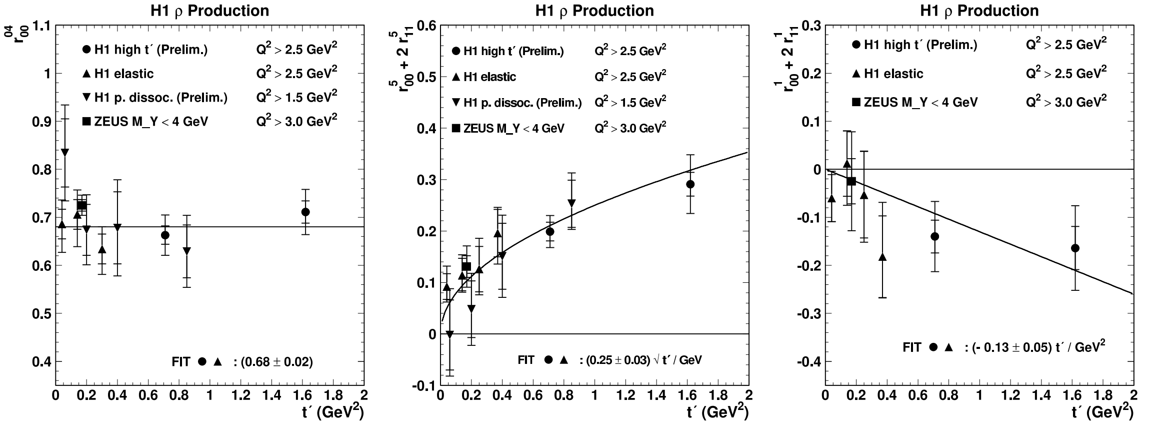

Figure 6: Spin density matrix elements of diffractive ρ^0 electroproduction measured by H1. a) r^{04}_{00}, b) $r^5_{00}+2r^5_{11}$ and c) $r^1_{00}+2r^1_{11}$ as a function of t'. Previous results at small t' [8] are also shown.

Figure 6 shows new H1 results on diffractive, i.e. elastic and proton dissociative ρ^0 electroproduction as a function of $t' = (p^T_e + P^T_{\rho^0})^2$ [9]. The previously measured elastic data at smaller values of t' are also shown. The element r^{04}_{00} (fig. 6a) shows a constant behaviour with t'. Its value is non-zero due to the contribution from longitudinally polarized photons in electroproduction. Significant helicity non-conservation is shown for the sum of $r^5_{00}+2r^5_{11}$ (fig. 6b) as extracted from the distribution of the azimuthal angle Φ. The size of the effect is attributed mainly to r^5_{00} which contains the single helicity flip amplitude T_{01}. At large t' the data follow a $\sqrt{t'}$ behaviour as suggested by [11]. The sum of $r^1_{00} + 2r^1_{11}$ (fig. 6c) is negative at large t'. The element r^1_{00} corresponds to the square of the single flip amplitude T_{01}. It should be zero in case of s-channel helicity conservation. From a calculation in pQCD it is expected to be negative [11]. The element r^1_{11} contains a double flip amplitude, $r^1_{11} \propto T_{1-1}T^*_{11} + T_{11}T^*_{1-1}$. Since r^1_{11} is positive or zero the sum gives information on the relative strengths of the $T_{01}T^*_{01}$ and $T_{11}T^*_{1-1}$ products of amplitudes.

Helicity measurements in ρ^0 and ϕ photoproduction (fig. 7) have been presented by ZEUS [4]. Here, the angular distributions in ϕ and θ are used to extract the elements a) r^{04}_{00}, b) $Re(r^{04}_{10})$ and c) r^{04}_{1-1}. The ρ^0 and ϕ results show good agreement with each other. The element r^{04}_{00} is close to zero, showing that the contribution of longitudinally polarized VMs is small at all t. $|T_{01}|^2$. In contrast, $Re(r^{04}_{10})$ depends linearly on $|T_{01}|$ and is therefore particularly sensitive to possible s-channel helicity non-conserving components in the data. Indeed, as shown in fig. 7b, the measured value of $Re(r^{04}_{10})$ shows significant deviations from zero. From $r^{04}_{1-1} \propto Re(T_{11}T^*_{1-1})$, the contribution from the double spin flip amplitude T_{1-1} can be determined. At large $|t|$, the data show evidence for r^{04}_{1-1} to be non-zero and negative (fig. 7c).

4. Summary and Conclusions

New results on diffractive vector meson production are presented. The kinematic region is extended to larger values of $|t|$. The new proton dissociation data reveal the features expected by perturbative QCD. At large $|t|$ the data follow a $|t|^{-n}$ dependence where $n \sim 3$ for ρ^0 and ϕ. For J/ψ production, which is fairly well described by calculations in leading order using a BFKL approach, the dependency is even flatter, $|t|^{-1.7}$. The results on vector meson production confirm that the variable $|t|$ provides a 'hard' scale for perturbative expansions in QCD. A comparison between the scales $|t|$ and Q^2, using the new proton dissociative data and earlier elastic data on the Q^2 dependence, indicates that the scales t and Q^2 do not play quite the same role. The photon-VM helicity transitions have been studied as a function of $|t|$. A comparison of the electroproduction results with calculations using perturbative QCD shows good agreement. More HERA data exploring the transition region between soft and hard diffraction with larger precision have been collected and will become available soon.

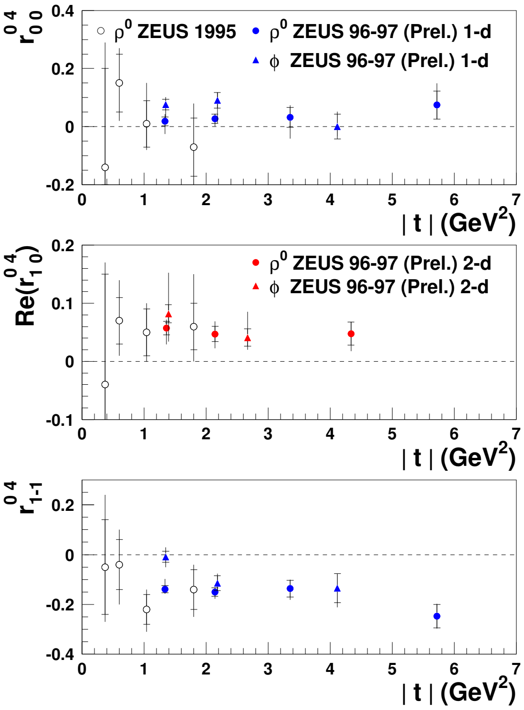

Figure 7: Spin density matrix elements of proton dissociative ρ^0 (circles) and ϕ (triangles) photoproduction as a function of $|t|$ measured by ZEUS. a) r^{04}_{00}, b) $Re(r^{04}_{10})$, c) r^{04}_{1-1}. Also shown are earlier results (open circles) [8].

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