At the HERA collider the experiments H1 and ZEUS have studied the exclusive production of vector mesons over a wide kinematical range. The recent measurements and their discussion within the framework of color dipole models and pQCD are reported.

1 Introduction

Exclusive photo- and electroproduction of light ($\rho, \omega, \phi$) and heavy ($J/\psi, \psi', \Upsilon$) vector mesons (VM) have been subject of intensive studies at HERA. The accelerator and its general purpose detectors H1 and ZEUS provide a unique opportunity to measure the exclusive diffractive production of vector mesons with different masses $M_{VM}$ in photo- and electroproduction.

1.1 Diffractive vector meson production

The process $ep \rightarrow e(VM)p$, drawn in fig. 1, can be described as a two step process. The incoming electron emits a photon. This photon fluctuates into a $q\bar{q}$ state which scatters with the proton by exchanging nothing but momentum.

The kinematical variables which are used to characterize the process are: the 4-momentum transfer squared $Q^2$ at the electron vertex, the center of mass energy of the $\gamma$-proton system $W$ and the 4-momentum transfer squared $t$ at the proton vertex. The dependences of the cross sections on these variables are presented in the ranges: $2 < Q^2 < 100 \, GeV^2$, $30 < W < 260 \, GeV$ and $|t| < 1 \, GeV^2$.

In the absence of a hard scale the colorless exchange between the vector meson and the proton can be modeled by a soft pomeron trajectory using the Regge approach. In this approach the cross section is predicted to rise slowly with $W$. In the presence of a hard scale, the vector meson production can be calculated using perturbative QCD (pQCD). In this case the colorless
exchange is modeled in leading order by a pair of gluons, the cross section is proportional to the square of the gluon density. This predicts a steep rise with increasing values of $W$.

2 $W$ dependence

For exclusive photoproduction ($Q^2 \approx 0 \text{ GeV}^2$) of vector mesons the $W$ dependence is shown in fig.2a). The lines indicate the rising of the cross sections assuming the form $W^\delta$. For the light vector mesons $\rho$, $\omega$ and $\phi$ the slope is $\delta \approx 0.22$. This value is very similar to the total photoproduction cross section and is predicted by the Regge approach. For the heavier vector mesons $J/\psi$, $\psi(2s)$ and $\Upsilon$ the observed slope is higher ($\delta \gtrsim 0.8$).

For the heavy vector mesons the masses of the charm and the bottom quarks provide a hard scale which allows the use of pQCD to calculate the cross sections. Such models are able to describe the $J/\psi$ cross section as it is shown in fig.2b). In particular the steep rise as a
function of the energy $W$ is well described by pQCD.

3 $Q^2$ and $|t|$ dependence

The $|t|$ dependence of the cross section for exclusive vector meson production is well described by the form $\frac{d\sigma}{dt} \propto e^{-b|t|}$ for small values of $t$ ($|t| < 1 \text{GeV}^2$). Fig.3a+b) show the dependence of the slope $b$ as a function of $Q^2$ for $\rho$ and $J/\psi$ in photo- and electroproduction. The slope of the $\rho$ cross section decreases with increasing $Q^2$. This indicates that the size of the interacting region is changing with $Q^2$. On the right hand side one can see that, in contrast to the $\rho$, the $J/\psi$ has no change in the slope with $Q^2$. The production mechanism for $J/\psi$ at the photoproduction limit is already the same as in the higher $Q^2 > 0$ range. This is interpreted as due to the fact that the $J/\psi$ mass already provides a hard scale at $Q^2 = 0$, in contrast to exclusive $\rho$ electroproduction.

In the diffractive picture $b$ is related to the radii of the colliding objects i.e. of the proton and the VM: $b \propto r_{VM}^2 + R_{	ext{proton}}^2$. The values of $b \approx 4.5 \text{ GeV}^{-2}$ measured in the hard regime implies a combined radius of the order of the size of the proton. This observation suggests that the transverse size of the $q\bar{q}$ fluctuation producing the $J/\psi$ in photoproduction and the $\rho$ at high $Q^2$ is smaller than that of the proton.

4 Decay angular distributions

The production and decay of a VM into a pair of oppositely charged particles can be described in terms of three angles: $\Phi_h$, the angle between the VM production plane and the lepton scattering plane; $\theta_h$ and $\phi_h$, the polar and azimuthal angles of the positively charged decay lepton in the $s$-channel helicity frame.

Under the assumption of $s$-channel helicity conservation (SCHC), the angular distribution for the decay of the VM depends only on two angles, $\theta_h$ and $\psi_h = \phi_h - \Phi_h$. From the $\theta_h$ distribution the spin density matrix element $T_{00}^{04}$ can be extracted which is proportional to the helicity amplitude $T_{00}$. $T_{00}$ corresponds to an amplitude, where a longitudinally polarized photon yields a longitudinally polarized VM. Also under the assumption of SCHC the ratio $R$ of cross sections for longitudinally and transverse polarized photons can be calculated using $T_{00}^{04}$: $(R = \frac{1}{2} \frac{r_{04}^{04}}{1 - r_{00}^{00}})$. This measurement for $\rho$ electroproduction is shown in fig.4). The left plot shows the rise of $R$.
Figure 4: a) $Q^2$ dependence of $R$ in $\rho$ electroproduction. b) $W$ dependence of $R$ in $\rho$ electroproduction in different bins of $Q^2$.

it indicates that the longitudinal dipole configuration becomes more dominant when increasing the value of $Q^2$. Within pQCD models a small dipole is most likely to be produced if the virtual photon is longitudinally polarized, which predicts that $|T_{00}|$ is the dominant amplitude.

Fig.4b) shows the ratio $R$ in $\rho$ electroproduction for different values of $Q^2$ regions as a function of $W$. The data is consistent with no $W$ dependence.

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