

**PRODUCTION OF VECTOR MESONS AND MEASUREMENT OF THE
HADRONIC COMPONENT OF PHOTON LIGHT-CONE WAVE FUNCTION
AT HERA**

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A detailed study of vector meson production (ϕ and J/ψ) in $e^\pm p$ collisions at HERA with the ZEUS and H1 detector has been performed. The cross sections are measured as a function of Q^2 , W and t . In this contribution, the results are summarised, compared to theoretical calculations and the dynamical picture emerging in perturbative QCD is highlighted. The measurement of the hadronic component of the photon light-cone wave function in the exclusive production of di-pions, $ep \rightarrow e\pi^+\pi^-p$ is also reported.

1 Exclusive vector meson production

The exclusive and inelastic production of vector mesons $ep \rightarrow eVX$, with $V = \phi, J/\psi$ and with X being either the scattered proton or the remaining hadronic system, has been extensively investigated at HERA.

In QCD-based models, the vector meson production is viewed as a sequence of processes: the virtual photon, γ^* , fluctuates into a $q\bar{q}$ pair which subsequently interacts with the proton and eventually forms a meson bound state. At high γ^*p center-of-mass energies, W , these successive processes are clearly separated in time (factorisation). The transverse size of the $q\bar{q}$ pair depends on the photon virtuality Q^2 and on the quark masses; for $Q^2 > \mathcal{O}(10)$ GeV² or for large masses, it is considerably smaller than the proton size. At these distances the strong coupling is small and perturbative QCD (pQCD) can be applied.

HERA offers the unique opportunity to study the dependences of these processes on several different scales: the mass of the meson, m_V , W , Q^2 and the four-momentum transfer squared at the proton vertex, t . Strong interactions can be investigated in the transition from the hard to the soft regime, where the confinement of quarks and gluons

occurs.

The dependence of the cross section on W is shown in Fig. 1 and 2 for exclusive vector meson production along with the total cross section. The W dependence for the lighter vector mesons (ρ , ω , ϕ) is similar to that of the total cross section, as expected from Regge theory. However there is a clear change as the vector meson mass increases: the J/ψ cross section has a steeper rise with W , which is a signature of a hard process. In pQCD models, the cross section is proportional to the square of the gluon density of the proton and the W dependence is then attributed to the rapid rise of the gluon density at small x (small $x \sim q^2/W$).

The DIS J/ψ data ^{1,3}, shown in Fig. 3, are precise enough to distinguish between different parton density function sets, but no discrimination can be made at present due to large theoretical uncertainties arising from higher-twist corrections, missing higher-order terms and skewed parton distributions. The data show that W dependence of the J/ψ cross section does not change with Q^2 ² and are well described by pQCD calculations ⁴. This kind of behaviour is not followed in the case of the ϕ meson where the W slope increases slightly with Q^2 ⁵ as it is for ρ mesons ^{6,7}.

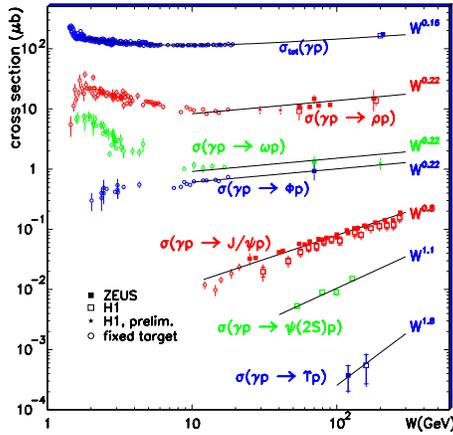


Figure 1. Compilation of cross sections for exclusive photoproduction of vector mesons as a function of W . The lines indicate a power law dependence, W^δ . The total photoproduction cross section is also shown.

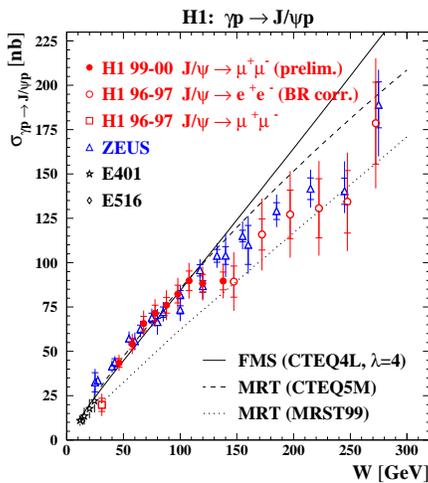


Figure 2. The J/ψ cross sections as a function of W . The experimental data are compared with pQCD models.

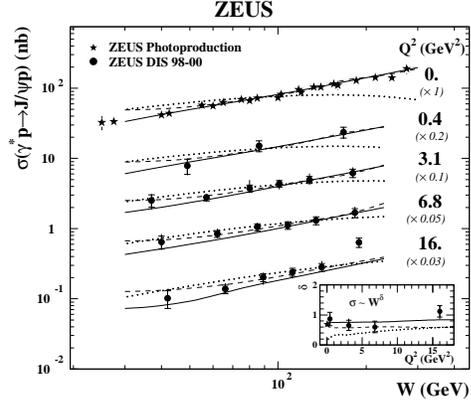


Figure 3. Exclusive J/ψ electroproduction cross section as a function of W for four values of Q^2 . The photoproduction results are also shown. The data are compared to MRT predictions obtained with different parametrisations of the gluon density (ZEUS-S solid line, CTEQ6M dashed and MRST02 dotted) and normalised to the photoproduction data at $\langle W \rangle = 90$ GeV. The insert shows the parameter δ as a function of Q^2 .

Measurements of the differential cross section, $d\sigma^{\gamma^*p \rightarrow \phi p}/dt$, measured as a function of t in the range $|t| < 0.6$ GeV² has also shown a variation of the slope for different values of Q^2 . A function of the form $d\sigma/dt = d\sigma/dt|_{t=0} \cdot e^{-b|t|}$ was fitted to the data and the results are shown in Fig. 4. The results are consistent with a global vector meson production scaling with $Q^2 + M_V^2$.

2 Inelastic J/ψ production

In the case of inelastic J/ψ production another quantity is also important: it is the inelasticity z that, in the proton rest frame, is equal to the fraction of the virtual photon energy taken by the J/ψ .

The direct and resolved photon processes can be described by the colour singlet (CS) or colour octet (CO) approach. In the former, the $c\bar{c}$ pair is formed in a colour singlet state with the J/ψ quantum numbers and is directly identified with the J/ψ physical state. In the CO approach, the $c\bar{c}$ pairs are produced in colour octet states which then

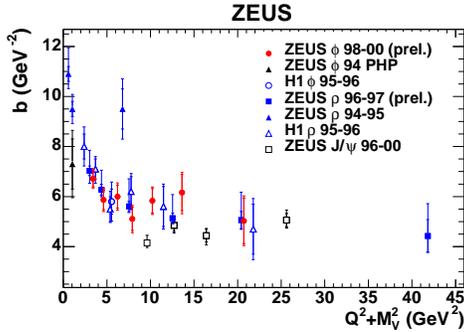


Figure 4. The b slope results of fits as described in the text, as a function of $Q^2 + M_V^2$, compared to previous H1 and ZEUS results.

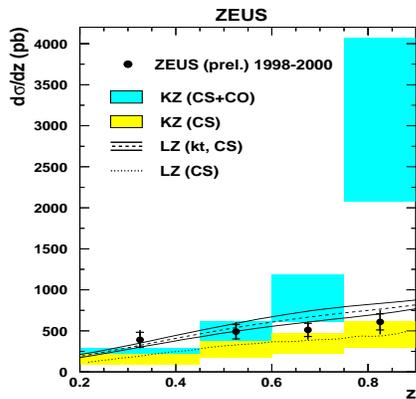


Figure 5. The plot shows the inelasticity differential cross section measured by the ZEUS experiment for $Q^2 > 2 \text{ GeV}^2$. The data are compared to the theoretical predictions described in the text.

evolve into J/ψ mesons via the radiation of soft gluons. The transition of the $c\bar{c}$ pair into the physical state is described in terms of long distance matrix elements tuned to J/ψ experimental data.

Inelastic J/ψ production in deep inelastic scattering regime probes non-relativistic QCD at a higher scale. Moreover for $Q^2 > 0$ the resolved photon processes, seen in photoproduction, are suppressed. Hence, in the DIS regime, no enhancement of the cross section at low z is expected.

The ZEUS measurement of the differen-

tial cross section with respect to z in the DIS regime⁸ is shown in Fig. 5. The data points are compared to a LO including both CS and CO or CS only matrix elements, identified by the labels KZ (CS+CO) and KZ (CS), respectively. As in the photoproduction regime^{9,10}, the strong rise of the CS+CO predicted cross section for $z > 0.75$ is not supported by data. A similar observation in the DIS regime was already reported by H1¹¹. Predictions based on the k_T factorisation approach, identified by the label LZ(kt, CS), are also shown. In this model, based on non-collinear parton dynamics governed by the BFKL evolution equations, effects due to the non-zero gluon transverse momentum are taken into account. The cross section is calculated as the convolution of an unintegrated gluon density¹² with CS off-shell matrix element. These calculations give reasonable description of the data both in normalization and shape.

3 Photon light-cone wave functions

The internal structure of the photon may be described using the light-cone wave function formalism (LCWF). The photon LCWF has both electromagnetic and hadronic components and can be studied for real or virtual photons. The electromagnetic component of the photon LCWF can be calculated within QED, while the hadronic one is model dependent.

In this contribution also the exclusive diffractive electroproduction of non-resonant $\pi^+\pi^-$ pairs has been reported. This is expected to be sensitive to the $|q\bar{q}\rangle$ component in the photon LCWF. In high energy interactions in the rest frame of the target, the valence Fock component dominates, while the other terms are suppressed according to counting rules¹⁴. In forward scattering, the momentum configuration of the interacting Fock state is preserved and therefore the final state is expected to reflect the kinematics

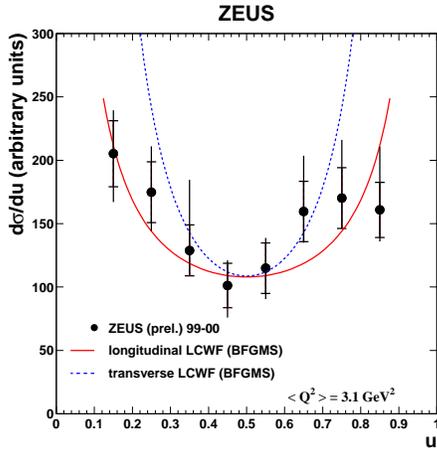


Figure 6. Differential cross section $d\sigma/du$ measured for $40 < W < 120$ GeV, $1.2 < M_{\pi\pi} < 5$ GeV, $2 < Q^2 < 5$ GeV² and $|t| < 0.5$ GeV². The data points are compared to the LCWF predictions, normalised to the data.

of the initial state.

Figure 6 shows the acceptance-corrected distribution of the longitudinal-momentum fraction carried by one of the pions, $(E_1 + p_{z_1})/(E_1 + E_2 + p_{z_1} + p_{z_2})$ where E_1, E_2 are the energies of the two pions and p_{z_1}, p_{z_2} are the corresponding momentum components determined with respect to the direction of the vector sum of the momenta of the two pions. The results are compared with LCWF predictions under the assumption that the measured cross section is proportional to the square of the photon wave function and that the pion momenta are equal to the momenta of the initial $q\bar{q}$ pair.

The data are compared to the prediction for both transversely- and longitudinally-polarised photons and are consistent with the latter.

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