HEAVY VECTOR MESON PRODUCTION AT HERA

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Representing the H1 and ZEUS collaborations

Recent results from the HERA experiments H1 and ZEUS on the exclusive production of heavy vector mesons V in ep collisions, i.e. the reaction $ep \to eVp$, are reviewed. The new measurements[1] include photoproduction of J/ψ at larger photon-proton centre-of-mass energy W than previously, more precise data on J/ψ electroproduction and $\psi(2S)$ photoproduction, and the observation of $\psi(2S)$ mesons in DIS at HERA. The measured cross sections are reasonably well described by QCD. Furthermore the first measurements of Υ photoproduction are reported.

1 Introduction

Since the first results obtained at the HERA ep collider became available, there is a renewed interest in elastic vector meson production (fig. 1a), especially at large Q^2 (Q^2 is minus the square of the exchanged photon 4-momentum) — more than a few GeV^2 — and large mass of the produced meson, e.g. J/ψ. This is reflected in a number of publications presenting new phenomenological models or refining existing ones (e.g. [2]), and in an effort from the experiments H1 and ZEUS to improve on the quality and kinematic reach of their data.

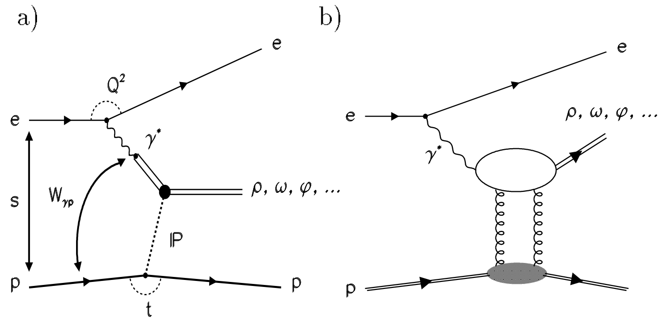

Figure 1: Diffractive vector meson production at HERA a) Regge-VDM model (including the definition of kinematic variables) b) pQCD models.

In fixed target experiments, the elastic reaction $\gamma p \to Vp$ ($V = \rho, \omega, \phi, \ldots$) has been successfully described by Regge theory together with the vector meson dominance model (VDM), exhibiting features typical for soft, hadron-like interactions. These are a small angle peak in the distribution of the vector meson scattering angle with respect to the photon beam direction ("elastic peak"), a steepening of this distribution with increasing energy ("shrinkage"), for $W \gtrsim 10\,\mathrm{GeV}$ a slow increase with energy of the cross section $\propto W^{4\epsilon} \simeq W^{4 \cdot 0.0808}$, and s-channel helicity conservation (SCHC).

However, the traditional VDM approach does not give a satisfactory description of J/ψ photoproduction: the cross section is smaller than the VDM prediction, and it increases significantly faster with energy than expected from soft pomeron exchange. This fast rise is predicted in models based on perturbative QCD, where the interaction is described as an exchange of two or more gluons in the t-channel (fig. 1b) between a virtual quark-antiquark pair and the constituents of the proton. In these models, the fast rise of the cross section with energy is driven by the rise of the gluon density in the proton towards smaller x. Calculations have also been performed for other processes where pQCD is thought to be applicable, i.e. elastic ρ production at high Q^2 and high $\mid t \mid$ (more than a few GeV^2).

In the following sections, new results from the H1 and ZEUS experiments on diffractive heavy vector meson photoproduction (i.e. $Q^2 \simeq 0$) and electroproduction ($Q^2 \gtrsim 1\,\mathrm{GeV}^2$) are shown. *Inelastic* J/ψ production, which is also intensively studied at HERA, is discussed in a separate paper [3].

2 J/ψ Photo- and Electroproduction

J/ψ production has been analysed in the decay channels $J/\psi \to \mu^+\mu^-, e^+e^-$, and results are published both for photoproduction [4,5] and at higher Q^2 [6,7]. Due to the small cross sections and limited acceptance of the *forward proton detectors*, none of the current analyses tags the outgoing proton to ensure an elastic reaction. The experimental method is rather to subtract inelastic backgrounds with the help of a Monte Carlo simulation that is shown to describe the properties of proton diffractive dissociation correctly. The excellent forward (proton beam direction) coverage of the H1 and ZEUS detectors is essential for this procedure.

The strong rise of the photoproduction cross section $\propto W^{0.9}$ as compared to fixed target results already reported in the first HERA measurements has been confirmed in the meantime using HERA data alone. In the model of Ryskin et al. [8] the cross section can directly be translated into a gluon density. The sensitivity to different gluon parameterizations is high, since the cross section is directly proportional to the *square* of the gluon density, but on the other hand there are significant normalization uncertainties in the calculation, preventing the process from being used to extract the gluon density in the proton.

The previous measurements of J/ψ photoproduction, covering the energy range $30 < W < 150$ GeV, are complemented by a new H1 analysis, based on data taken in 1997 and corresponding to an integrated luminosity of $12\,\mathrm{pb}^{-1}$, made possible by utilising detector components able to identify the decay products of the J/ψ mesons travelling in the backward direction (positron beam direction). The decay $J/\psi \to e^+e^-$ is used. Two separate event selections have been carried out, which cover two different ranges of W. The selection covering the W range between 135GeV and 210GeV requires one electron to be observed as a track in the central tracking detector with polar angle $80° < \theta < 155°$ which is identified as an electron in the liquid argon calorimeter. The second decay electron is observed as an electromagnetic cluster with $E > 3.5$ GeV in the backward electromagnetic calorimeter (Spacal[9]). For the range $210 < W < 285$GeV both electrons are observed as electromagnetic clusters with $E > 4.2$ GeV (one cluster with $E > 6.3$ GeV) in the Spacal. For a precise measurement of the polar angle θ of the electrons the backward silicon tracker (BST [10]) is utilised. In addition this device is used to separate clusters originating from photons and clusters originating from electrons which cause a track in the BST. In this way, background from the QED Compton process can be reduced significantly.

The dependence of the cross section on the photon-proton centre-of-mass energy, W, is thus determined over the extended range $30 < W < 285$ GeV, and shown in figure 2. A fit to the energy dependence of the cross section measured by H1 and ZEUS of the form W^δ yields $\delta = 0.80 \pm 0.10$, significantly steeper than predicted by soft pomeron exchange, but qualitatively in agreement with a perturbative QCD calculation [11] in which the rise reflects the increasing gluon density in the proton as the momentum fraction x decreases.

The presence or absence of *shrinkage* of the width of the diffraction peak with energy — indicated by a value of the slope of the Pomeron trajectory, α', of about $0.25\,\mathrm{GeV}^{-2}$ [15] — is controversial in the case of J/ψ production. While the ZEUS analysis shows evidence for the absence of shrinkage ($\alpha' = 0.015 \pm 0.065\,\mathrm{GeV}^{-2}$, fig. 3 left), H1 favours the shrinkage scenario while not being significant (fig. 3 right). The difference between the two analyses that causes the discrepancy is the selection and treatment of the fixed target data that are used, which may suffer from inelastic backgrounds and target effects. HERA data alone are not yet precise enough to allow a definite conclusion.

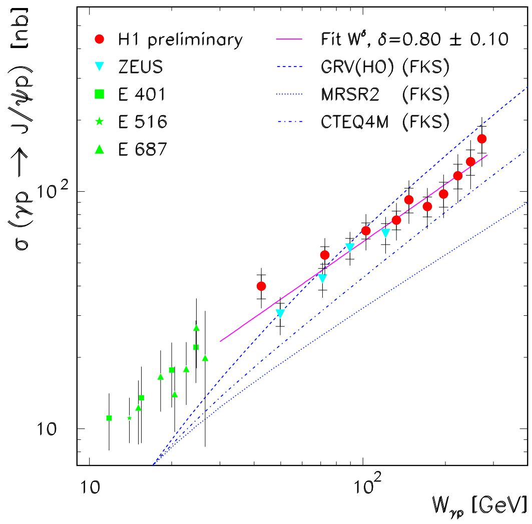

Figure 2: Cross section for the reaction $\gamma p \to J/\psi p$ as a function of the photon-proton centre-of-mass energy as measured by H1, ZEUS [5] and fixed target experiments [12,13,14]. A fit of the form W^δ to the HERA data is indicated, along with predictions of QCD calculations by Frankfurt, Koepf and Strikman [11] for three parameterizations of the gluon density in the proton.

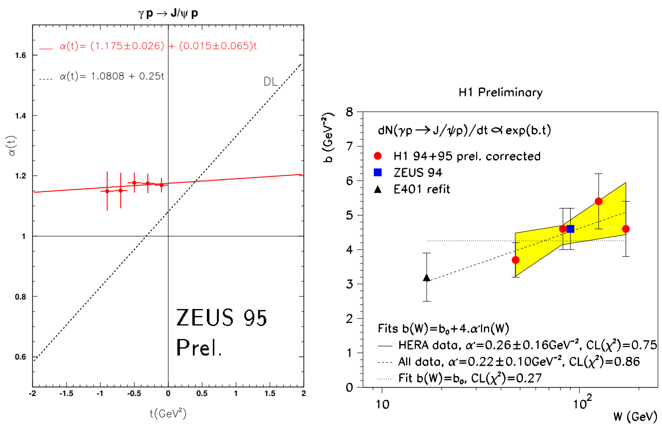

Figure 3: Left: Fit of the Pomeron trajectory; data from H1, ZEUS, EMC and E401 are included (see [16] for details). For comparison, the result of Donnachie and Landshoff [15] of a fit to hadron-hadron scattering data is also shown. Right: Slopes b from fits to differential distributions $d\sigma(\gamma p \to J/\psi p)/dp_t^2$ of the form e^{bt} as measured by the HERA experiments H1 and ZEUS, and by E401. The band shows a fit with 1σ uncertainties of the form $b(W) = b_0 + 4\alpha' \log W$ to the HERA data alone. The dashed line indicates the best fit including the E401 measurement. Also shown is a fit to a constant value.

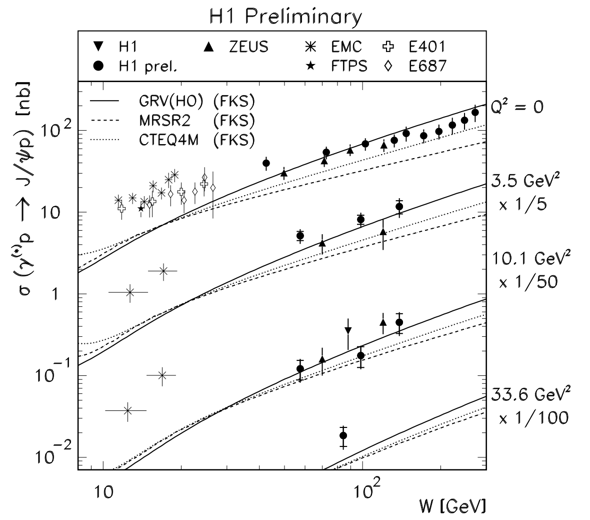

Figure 4: Cross sections for exclusive J/ψ production as a function of W at different values of Q^2, measured at HERA and in fixed target experiments. Data for $Q^2 > 0\,\mathrm{GeV}^2$ have been scaled by 5, 50, and 100 as indicated. The lines are results of calculations from Frankfurt, Koepf and Strikman [11] using several recent parameterizations of the proton structure function.

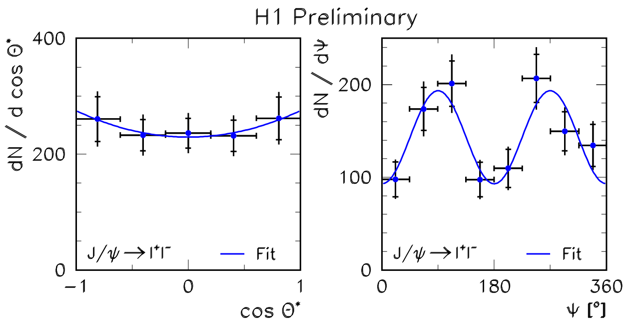

Figure 5: Angular distributions for exclusively produced J/ψ mesons in the kinematic range $40 < W < 160\,\mathrm{GeV}$ and $2 < Q^2 < 80\,\mathrm{GeV}^2$: (a) $\cos\theta^*$, the J/ψ decay angle in the helicity frame; (b) Ψ, the polarization angle in the $\gamma^* p$ centre-of-mass frame. The lines are fits to the data with R as a free parameter.

Going from photoproduction to high Q^2 introduces another scale into the consideration besides the vector meson mass. The virtual photon proton cross section falls steeply as a function of Q^2, and can be parameterized following a $(Q^2 + m_\psi^2)^{-n}$ ansatz with $n \simeq 2$, comparable to results for lighter vector mesons. New results exist on the exclusive production of the J/ψ meson in deep-inelastic ep scattering both from H1 and ZEUS and can be confronted with pQCD expectations [11]. Data from the years 1995 (ZEUS) and 1995 to 1997 (H1) are used. Cross sections for the process $\gamma^* p \to J/\psi\, p$ are extracted as a function of W in different Q^2 domains, extending the precision and kinematic reach of previous measurements [6]. The results are compared to the predictions in figure 4, and show reasonable agreement.

With the new data, an analysis of the helicity structure of J/ψ production in DIS becomes possible. A number of angles are defined as follows [17]. θ^* and ϕ are respectively the polar and azimuthal angles of the direction of flight of the positive decay lepton in the helicity frame, i.e. in the J/ψ rest frame, with the z-axis defined as the direction of the J/ψ in the $\gamma^* p$ centre-of-mass frame, and the y-axis perpendicular to the J/ψ production plane. Φ is the angle between the J/ψ production plane and the electron scattering plane in the $\gamma^* p$ centre-of-mass frame. The polarization angle Ψ is defined as $\phi - \Phi$.

If the helicity of the virtual photon is retained by the J/ψ meson, i.e. the s-channel helicity conservation (SCHC) hypothesis is correct, the angular distribution is only a function of θ^* and Ψ:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\cos\theta^*\,\mathrm{d}\Psi} \propto 1 + \cos^2\theta^* + 2\epsilon R \sin^2\theta^* - \epsilon \sin^2\theta^* \cos 2\Psi + \sqrt{2\epsilon R(1+\epsilon)}\cos\delta\cos\Psi\sin 2\theta^*$$

where R is the ratio σ_L/σ_T of the contributions to the cross section from longitudinally and transversely polarized photons, δ is the phase difference between the longitudinal and transverse contributions, and ϵ is the polarization parameter, with a mean value of 0.99 in the kinematic range of this analysis. The acceptance-corrected $\cos\theta^*$ and Ψ distributions found by H1 are shown in figure 5. Fits with R as a free parameter yield for the $\cos\theta^*$ distribution $R = 0.34^{+0.27}_{-0.19}$ at $Q^2 = 8.3\,\mathrm{GeV}^2$. The result obtained from the Ψ distribution is compatible within the experimental uncertainty, indicating compatibility with SCHC. The ZEUS result from the fit of the $\cos\theta^*$ distribution is $R = 0.41^{+0.45}_{-0.52}$ at $Q^2 = 5.9\,\mathrm{GeV}^2$, compatible with the H1 measurement. The measured values for R are significantly smaller than those measured for ρ production at a similar Q^2.

3 $\psi(2S)$ Photo- and Electroproduction

The presence of a radial node in the $\psi(2S)$ wavefunction leads to a relative suppression of the $\psi(2S)$ with respect to the J/ψ. Using colour dipole phenomenology, a prediction for the ratio of the elastic photoproduction cross sections of 0.17 is obtained [18]. Studying the ratio of cross sections provides a test of the model which is free of many normalisation uncertainties. A new ZEUS measurement (fig. 6 left) of $R = 0.16 \pm 0.02 \pm 0.04$, using the direct decay $\psi(2S) \to \mu^+\mu^-$, confirms the expectation.

The first measurement of quasi-elastic[a] production

[a] i.e. including processes where the proton dissociates

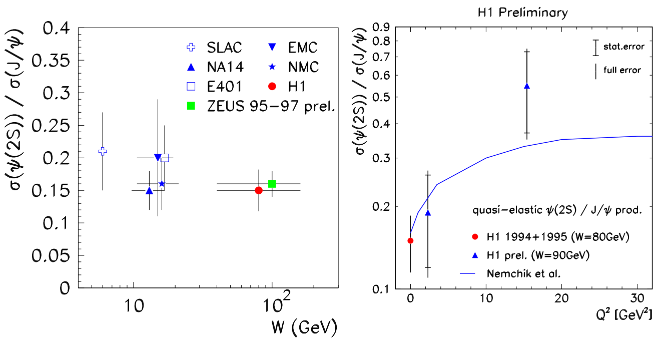

Figure 6: Ratio of cross sections for $\psi(2S)$ over J/ψ production as a function of W (left) and Q^2 (right).

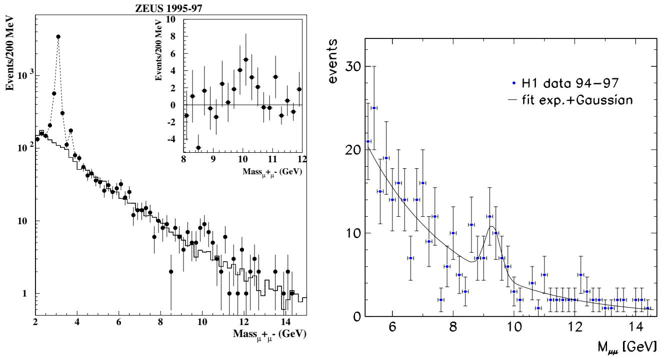

Figure 7: The invariant mass spectra of dimuon events observed in the ZEUS (left) and H1 (right) detectors.

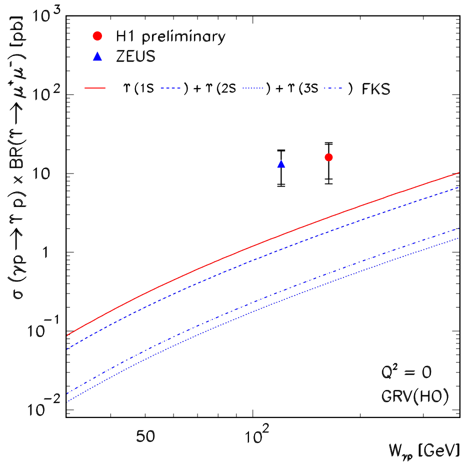

Figure 8: Cross section times branching ratio into two muons for the reaction $\gamma\, p \to \Upsilon\, p$ measured by H1 and ZEUS [21], and the pQCD expectation from [11].

of the $\psi(2S)$ meson in DIS at HERA has been presented by H1. Using the decay channel $\psi(2S) \to J/\psi\, \pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$, the ratio of the cross sections for quasi-elastic $\psi(2S)$ and J/ψ production is extracted for two values of Q^2 from 23 pb^{-1} of data taken in 1995 to 1997 (fig. 6 right). There is an indication for a rise of this ratio with Q^2, as is expected e.g. in the Colour Dipole Model [19].

4 Υ Photoproduction

Measurements of diffractive photoproduction of J/ψ mesons at HERA demonstrate cross sections of the order of 100 nb at a photon proton centre of mass energy of 100 GeV. Predictions from models based on perturbative QCD [11,19] lead to a cross section for Υ production about three orders of magnitude lower. Since a recent H1 measurement of inclusive photoproduction of b quarks [20] yields a higher cross section than anticipated, the measurement of Υ mesons is interesting.

Both H1 and ZEUS investigated the dimuon invariant mass spectrum (fig. 7) above the $c\bar{c}$ resonances, using an integrated luminosity corresponding to 35 pb^{-1} (H1) and 43 pb^{-1} (ZEUS) respectively. An enhancement in the mass region of the Υ resonances is seen by both experiments; note that the experimental resolution does not allow to separate the $1S$, $2S$ and $3S$ states. The non-resonant part of the mass spectrum is due to muon pair production from two-photon processes; subtracting this background using a Monte Carlo simulation (ZEUS) or a fit procedure (H1), and correcting for acceptance and efficiencies, the photoproduction cross section for the three states is extracted as $\sigma(\gamma\, p \to \Upsilon\, p) \times \mathrm{BR}(\Upsilon \to \mu^+\mu^-) = 13.3 \pm 6.0^{+2.7}_{-2.3}$ pb (ZEUS) at $W = 120$ GeV and $\sigma(\gamma\, p \to \Upsilon\, p) \times \mathrm{BR}(\Upsilon \to \mu^+\mu^-) = 16.0 \pm 7.5 \pm 4.0$ pb (H1 preliminary) at $W = 160$ GeV. Theoretical expectations [11,19] lie about two standard deviations below these measurements, see figure 8. Taking into account the different production and branching fractions of the three Υ states results in $\Upsilon(1S)$ photoproduction cross sections of $\sigma(\gamma\, p \to \Upsilon(1S)\, p) = 375 \pm 170^{+75}_{-64}$ pb (ZEUS) and $\sigma(\gamma\, p \to \Upsilon(1S)\, p) = 450 \pm 240$ pb (H1 preliminary). The ratio $\sigma(\gamma\, p \to \Upsilon(1S)\, p)/\sigma(\gamma\, p \to J/\psi\, p)$ is measured by ZEUS to be $4.8 \pm 2.2^{+0.7}_{-0.6} \times 10^{-3}$. In figure 9 the $\Upsilon(1S)$ cross section is shown in comparison to the results obtained for other vector mesons.

5 Conclusions

The start of the 'high-luminosity-era' of HERA opens up new possibilities for heavy quark and diffractive physics. The amount and precision of the new data allow to test QCD predictions for the exclusive production of heavy vector mesons. In the case of J/ψ and $\psi(2S)$ photo- and electroproduction, a qualitative description is achieved, while there is an indication for an anomalously large Υ cross section.

Many of the measurements presented here, e.g. of Υ production or of the helicity structure of J/ψ production,

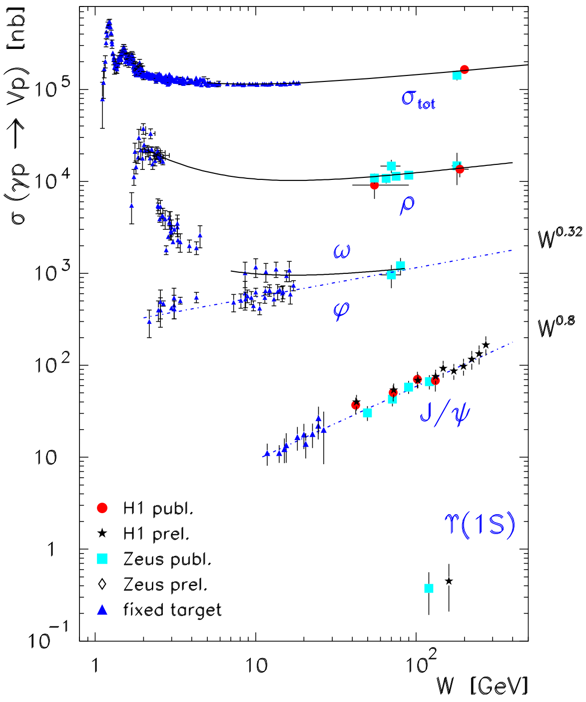

Figure 9: Summary of vector meson photoproduction cross sections measured at HERA and in fixed target experiments.

are severely statistically limited, and will profit from the HERA luminosity upgrade programme.

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1. Contributed papers to this conference:
   H1 Collaboration, 'Diffractive Charmonium Production in Deep Inelastic Scattering at HERA', 'Energy Dependence of the Cross Section for the Exclusive Photoproduction of J/ψ Mesons at HERA' and 'Shrinkage in Exclusive J/ψ Production' (572);
   H1 Collaboration, 'Photoproduction of Υ Mesons at HERA' (574);
   ZEUS Collaboration, 'Exclusive Electroproduction of ρ and J/ψ Mesons at HERA' (792);
   ZEUS Collaboration, 'Measurement of Elastic Υ Photoproduction at HERA' (791);
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