Heavy Vector Meson Production at HERA

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The production of J/ψ, $\psi(2S)$ and Υ mesons in positron-proton collisions at a centre-of-mass energy of 300 GeV has been studied by the H1 and ZEUS experiments at the HERA collider. Results are obtained over large ranges in the exchange photon virtuality, the virtual photon-proton centre-of-mass energy, and the inelasticity of the production. Models incorporating perturbative QCD calculations are confronted with the experimental data.

1. INTRODUCTION

The H1 [1] and ZEUS detectors measure the products of head-on collisions between positrons of 27.5 GeV and protons of 820 GeV energy, produced by the HERA collider. Heavy quark (charm and beauty) production at HERA is dominantly a result of the exchange of a single virtual photon between the positron and proton so that the positron can be regarded as a source of photons which subsequently interact with the proton. Since the photon flux spectrum is known, for the purpose of heavy quark production HERA can be regarded as a photon-proton collider where the photons can have virtuality ranging from $Q^2 = 0$ GeV^2 (photo-production) to 90000 GeV^2, and the photon-proton invariant mass ranges from threshold up to $W = 300$ GeV. Large photon virtualities are highly suppressed so that all current results are restricted to the domain where Q^2 is less than about 100 GeV^2.

Due to the large heavy quark masses and the fact that the proton contains no valence heavy quarks a short distance partonic interaction is always involved which produces a heavy quark-anti-quark pair, and which is usually initiated by a gluon from the proton. Therefore perturbative quantum-chromodynamics (pQCD) calculations should be applicable, and the production cross-sections should be sensitive to the gluon content of the proton. In the case of heavy vector meson production, charmonium and bottomonium, the heavy quark-anti-quark pair emerges in a well-defined and easily measurable state.

The dominant production mechanism for heavy vector mesons in virtual photon-proton collisions depends upon the elasticity, quantified by the Lorentz invariant $z \equiv p_V.p/q.p$ where p_V, q and p are the four-momenta of the vector meson and the incoming photon and proton respectively. At the lowest values of z resolved photon production dominates, in which a parton from the photon participates in the hard sub-process. For z between about 0.4 and 0.9 the photon-gluon fusion process dominates — the photon directly enters the hard sub-process. At z approaching 1 the production is of a diffractive nature — the produced vector meson is separated by a large rapidity gap from the dissociated proton or the proton remains intact. The latter process, $\gamma^* p \to V p$, is called exclusive production and is possible because the vector mesons carry the same quantum numbers as the photon.

As yet, no results from the resolved production of heavy vector mesons have been obtained. Results on direct inelastic production of J/ψ mesons are presented in section 2 and compared to pQCD calculations in the non-relativistic factorisation approach. The exclusive production of J/ψ, $\psi(2S)$ and Υ mesons is discussed in later sections and results are discussed in the contexts of a phenomenological description in the framework of Regge theory, and perturbative quantum chromodynamics calculations.

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2. INELASTIC J/ψ PRODUCTION

Both the H1 and ZEUS experiments have measured the differential cross-sections for the photo-production ($Q^2 = 0$) of J/ψ mesons as a function of elasticity, z, photon-proton centre-of-mass energy, W, and the squared transverse momentum of the J/ψ mesons, p_T^2, based on data recorded in 1994 and 1995 [2,3]. Recently results on the inclusive production of J/ψ mesons for $2 < Q^2 < 80$ GeV^2, using data collected between 1995 and 1997, have been obtained.

Predictions are available from pQCD calculations in the non-relativistic factorisation approach [4]. The pQCD short distance interaction producing a charm-anti-charm pair in a particular spin, angular momentum and colour configuration is factorised off from the long distance matrix elements describing the transition from the $c\bar{c}$ pair into a J/ψ meson. The long distance matrix elements are not calculable but are extracted from fits to data. Until unexpectedly high cross-sections for direct charmonium production were measured at the Tevatron [5], only the case in which the short distance interaction produces a $c\bar{c}$ pair in a colour singlet (CS) state had been considered. It was found that the data could be explained by considering also production of colour octet (CO) states if the long distance transition to a J/ψ meson from a CO state is suppressed by about one order of magnitude with respect to that from a CS state. The HERA data provide a vital complementary test for the model, since the relative contributions from the various $c\bar{c}$ states will be different than at the Tevatron.

Figure 1 shows the differential cross-section as a function of z for the photo-production of J/ψ as measured by H1 and ZEUS, which is rather flat over the kinematic range of the measurement. An early prediction in which both CS and CO matrix elements were calculated at $\mathcal{O}(\alpha_S^2)$ and long distance matrix elements were extracted from fits to the Tevatron data is indicated by the upper side of the shaded band [6]. It was subsequently noted that the long distance matrix elements would be significantly suppressed if initial state gluon radiation were taken into account [7] — a revised prediction is shown as the lower side of the band.

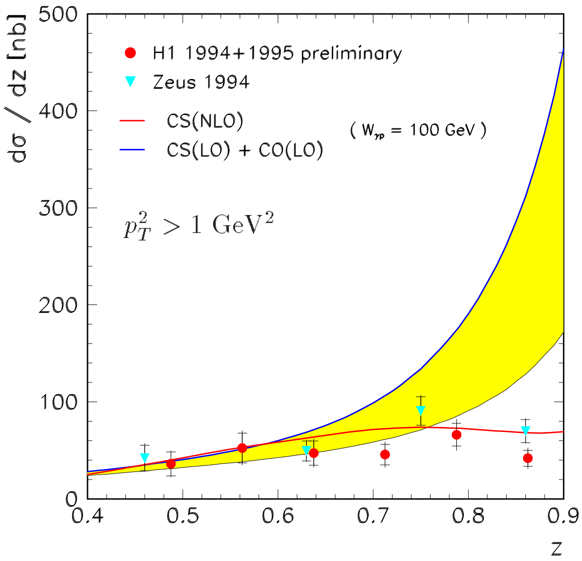

Figure 1. Inelastic photo-production of J/ψ: elasticity dependence of cross-section

Further theoretical consideration has led to the conclusion that the z distribution for the CO matrix elements cannot be reliably calculated, not least because the transition to the J/ψ meson necessarily involves some unknown amount of momentum loss by radiation which causes a shift in z. Thus the original apparent discrepancy between the model prediction and the HERA data is no longer considered a sign of a breakdown of the model. Also indicated in figure 1 is a prediction at $\mathcal{O}(\alpha_S^3)$ considering only the CS contribution which matches the data rather well [8]. This is also the case for the p_T^2 and W dependences of the cross-section for photo-production of J/ψ. It should be noted that the $\mathcal{O}(\alpha_S^3)$ corrections are significant, as is particularly visible in the p_T^2 predictions.

Figures 2(a-d) show the differential positron-proton cross-sections for inclusive J/ψ production in the kinematic range $2 < Q^2 < 80$ GeV^2 and $40 < W < 180$ GeV as measured in the H1 experiment. The open points are the inclusive measurements whereas the closed points are the result of

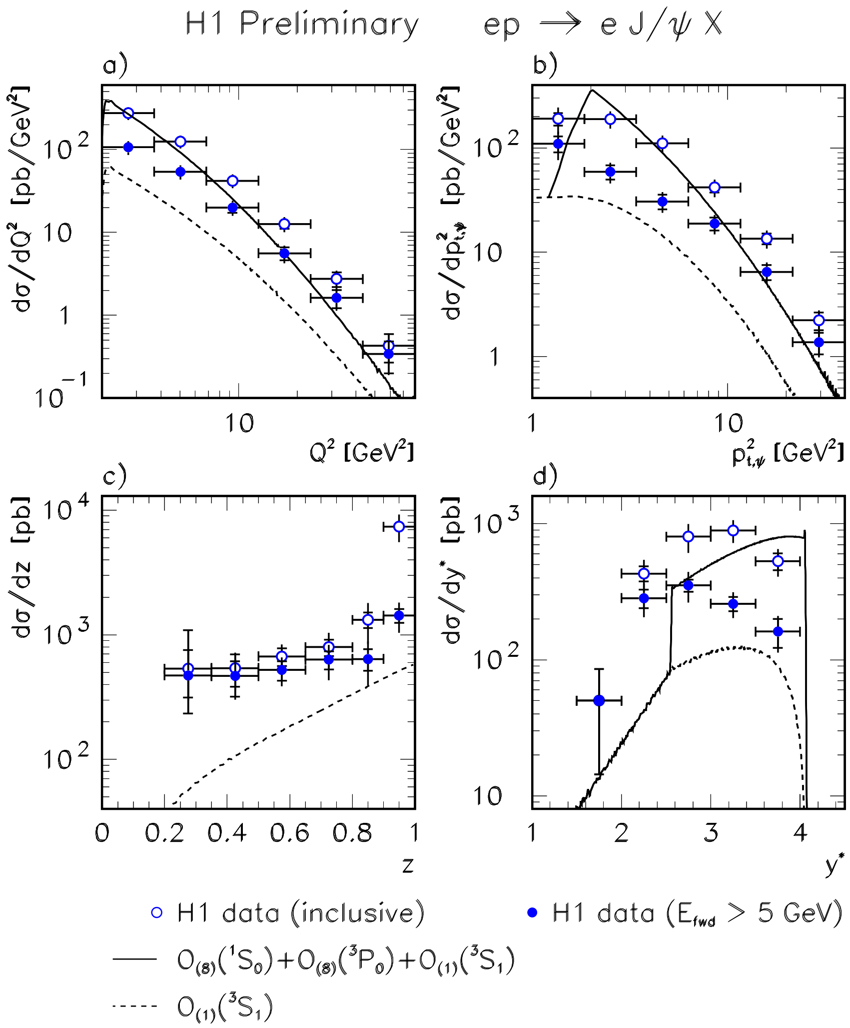

Figure 2. Inelastic electro-production of J/ψ: differential cross-sections with respect to a) photon virtuality, b) J/ψ transverse momentum in the laboratory frame, c) elasticity, d) rapidity in the virtual-photon-proton centre-of-mass frame.

suppressing diffractive contributions by insisting that at least 5 GeV energy has been deposited in the region of the H1 calorimeter close to the exiting proton ('forward') direction. This condition is seen to remove events particularly at high z where the diffractive contribution is expected. Indicated are the predictions considering only the CS contribution at $\mathcal{O}(\alpha_S^2)$ (dashed line), and adding in CO contributions at $\mathcal{O}(\alpha_S)$ [9]. The CS prediction for the cross-section is too small. Whilst the CO corrections recover the magnitude to some extent, the shape clearly does not match the data. It should be noted that the colour octet contributions are calculated at leading order so that all the momentum entering the hard sub-process is transferred to the J/ψ. This leads to the sharp edges in the p_T^2 and y^* predictions, and also renders a prediction of the z distribution meaningless. In the photo-production case, where higher orders in α_S have been calculated, it has been demonstrated that they are important. Hence there is a clear need for the calculation to be extended to higher orders at non-zero Q^2.

Further light will be shed on this calculational approach with future measurements of resolved photon production of J/ψ mesons and helicity studies in particular.

3. EXCLUSIVE CHARMONIUM PRODUCTION

The reaction $\gamma^* p \to Vp$, where V is a J/ψ or $\psi(2S)$ meson, can be considered as a three stage process at HERA energies: the fluctuation of the virtual photon into a $c\bar{c}$ pair, the interaction of the $c\bar{c}$ pair with the proton, and the formation of the vector meson from the emerging $c\bar{c}$ pair. Calculations of the $c\bar{c}p \to c\bar{c}p$ sub-process in pQCD have been performed which correspond to (colourless) gluon ladder exchange and relate the cross-section at a given W to the square of the gluon density in the proton at a momentum fraction $x_g \approx (M_V^2 + Q^2)/W^2$ [10,11].

A phenomenological model for this process can be derived using the vector meson dominance model (VDM) to describe the V content of the photon, and Regge theory to describe the energy dependence of the elastic V scattering off the proton. For the photo-production of light vector mesons and total hadronic cross-sections a good description of the data is obtained by the exchange of a universal soft pomeron — a linear Regge trajectory with intercept about 1.08 and slope of about 0.25 GeV^{-2} [12].

Figure 3 shows measurements of the virtual-photon proton cross-section for the production of J/ψ mesons as a function of W for various Q^2, as measured in the H1 [2] and ZEUS [13] experiments and compared to fixed target experiments [14]. In the photo-production case the measurements span a large range in W and a steep rise of the cross-section, approximately propor-

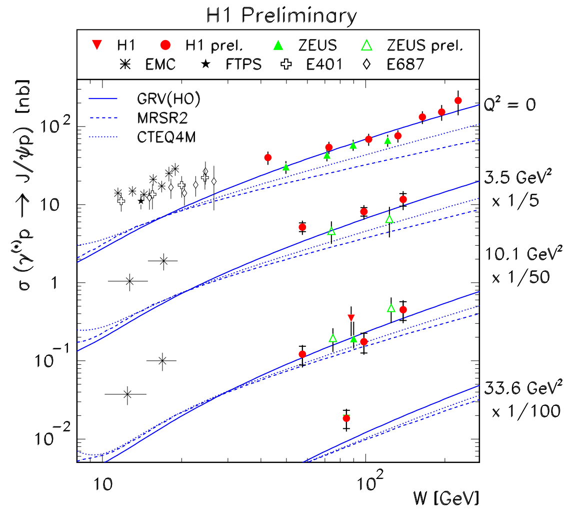

Figure 3. Exclusive J/ψ production: virtual photon-proton cross-section as a function of W at various Q^2.

tional to W, is observed. The results for higher Q^2 suggest a similar rise. This is inconsistent with soft pomeron exchange for which a rather weak energy dependence is expected. The exchange is therefore referred to as the 'hard pomeron', presumably having a larger intercept than the soft pomeron, and the hardness is attributed to the large scale of the vector meson mass. Similar behaviour is observed for light vector mesons at large Q^2. It has been postulated that the present measurements contain contributions from the soft as well as a hard pomeron — the soft contribution would then only become negligible at even higher energies [15].

In this context it is interesting to regard the exchange responsible for J/ψ photo-production as a linear Regge trajectory and to measure the slope. This is done by fitting the HERA data on the p_T^2 distributions of the cross-sections to an exponential form $e^{-bp_T^2}$ and plotting b as a function of W. The slope, α', is then derived from a fit of the form $b = b_0 + 4\alpha' \log W$, and a non-zero result (as for the soft pomeron) is called 'shrinkage'. The result is shown in figure 4 and gives an α' value

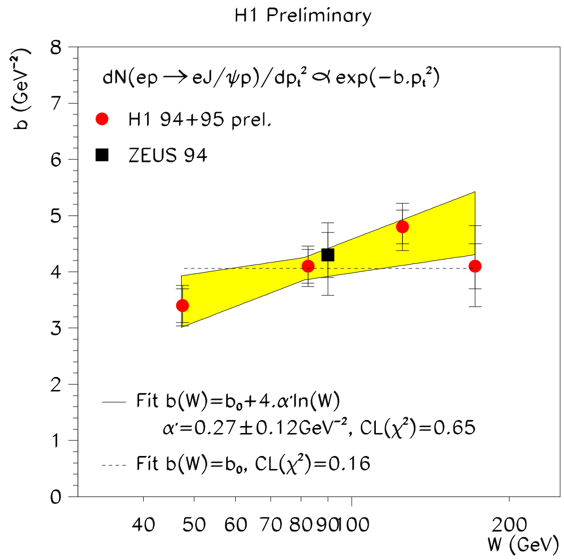

Figure 4. Exclusive J/ψ production: b-slope as a function of W with Regge-type fits.

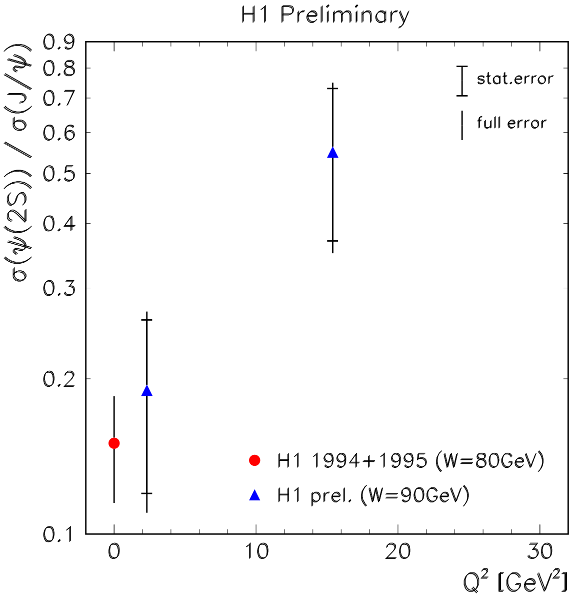

Figure 5. Diffractive charmonium production: ratio of the ψ(2S) to J/ψ cross-sections.

compatible both with that for the soft pomeron, and also with the no shrinkage scenario.

Also shown in figure 3 are the results of calculations based on pQCD for three different parametrisations of the gluon density in the proton [11]. Qualitatively they describe the steep rise of the cross-section, which in this picture is a consequence of the proliferation of gluons in the proton at small momentum fractions, x_g. Note that the calculations are expected to fail at the low energies where fixed target measurements have been made.

Diffractive ψ(2S) meson production has been observed. The ratio of the ψ(2S) and J/ψ cross-sections as a function of Q^2 is shown in figure 5. A hint of a rise with increasing Q^2 is seen, as is expected in models which take into account the forms of the radial wave-functions of the 1S and 2S charmonium states. The radial separation of the $c\bar{c}$ pair emerging from the $c\bar{c}p \to c\bar{c}p$ subprocess is smaller for larger Q^2, and hence the production rate for a vector meson becomes sensitive to the radial wave-function nearer to the origin. At small Q^2 the radial wave-function away from the origin is probed, and the 2S production is suppressed with respect to 1S because of the node [16,17].

4. EXCLUSIVE Υ PRODUCTION

Evidence for Υ meson production at HERA is seen in the invariant mass distributions for muon pairs in both the H1 and ZEUS experiments. The distribution measured by ZEUS is shown in figure 6 where the J/ψ, ψ(2S) and Υ resonances are visible above a continuum background which is dominated by QED processes. The experimental resolution on the invariant mass is such that the 1S, 2S and 3S Υ states cannot be distinguished.

The cross-section for the exclusive photoproduction process $\gamma p \to \Upsilon p$ has been determined and is shown in figure 7. It is suppressed by about a factor of 150 with respect to the equivalent cross-section for J/ψ production. The predictions from the same pQCD calculation as shown in figure 3 for the J/ψ case are indicated. They un-

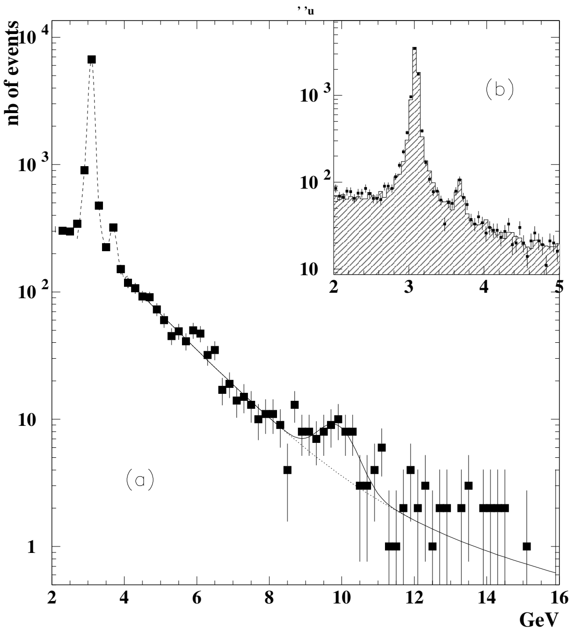

Figure 6. Muon pair invariant mass distribution with J/ψ, $\psi(2S)$ and Υ resonances (ZEUS prel.).

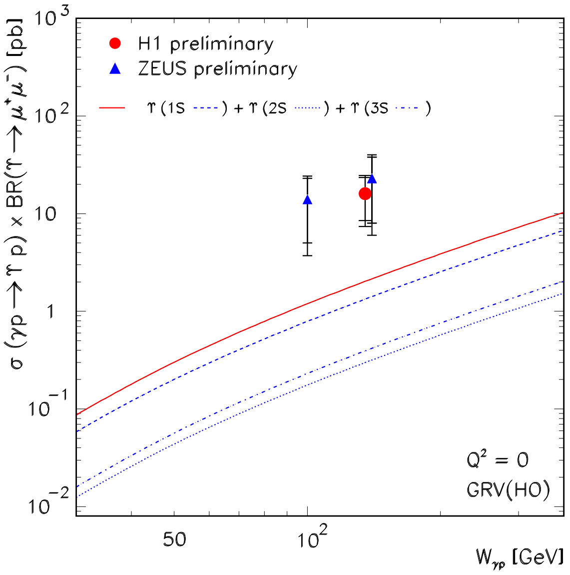

Figure 7. Exclusive Υ production: cross-section with pQCD predictions.

derestimate the measured cross-section.

5. CONCLUSION

Heavy vector meson production at HERA is a unique laboratory for testing QCD and models of hadronic interactions. Studies of inelastic J/ψ production indicate that there is still some way to go in understanding how to calculate such processes in the framework of the non-relativistic QCD factorisation approach. On the other hand, in photo-production a calculation only accounting for colour singlet configurations of the charm-anti-charm pair reproduces the data convincingly.

Exclusive charmonium production at HERA represents the unambiguous observation of a hard pomeron which, it appears, may be calculable using perturbative QCD. If this proves to be the case then these are measurements which are extremely sensitive to the gluon density in the proton. The new results on Υ production open up new possibilities for testing the models.

There lies a rich future ahead for studies of heavy vector meson production at HERA. Most studies remain statistics limited so that the HERA luminosity upgrade in the year 2000 will enable greatly improved precision in all results, and an increased reach in the kinematic domain of study.

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