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Measurement of the cross section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in deep inelastic exclusive ep scattering at HERA

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Abstract. The exclusive deep inelastic electroproduction of $\psi(2S)$ and $J/\psi(1S)$ at an ep centre-of-mass energy of 317 GeV has been studied with the ZEUS detector at HERA in the kinematic range $2 < Q^2 < 80\,\mathrm{GeV}^2$, $30 < W < 210\,\mathrm{GeV}$ and $|t| < 1\,\mathrm{GeV}^2$, where Q^2 is the photon virtuality, W is the photon–proton centre-of-mass energy and t is the squared four-momentum transfer at the proton vertex. The data for $2 < Q^2 < 5\,\mathrm{GeV}^2$ were taken in the HERA I running period and correspond to an integrated luminosity of $114\,\mathrm{pb}^{-1}$. The data for $5 < Q^2 < 80\,\mathrm{GeV}^2$ are from both HERA I and HERA II periods and correspond to an integrated luminosity of $468\,\mathrm{pb}^{-1}$. The decay modes analysed were $\mu^+\mu^-$ and $J/\psi(1S)\pi^+\pi^-$ for the $\psi(2S)$ and $\mu^+\mu^-$ for the $J/\psi(1S)$. The cross-section ratio $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ has been measured as a function of Q^2, W and t. The results are compared to predictions of QCD-inspired models of exclusive vector-meson production.

Exclusive electroproduction of vector mesons in deep inelastic scattering at high energies, $ep \rightarrow eVp$, where V denotes a vector meson, may be described as a multi-step process. The electron emits a virtual photon, γ^*, with virtuality Q^2 and $\gamma^* p$ centre-of-mass energy W, the virtual photon fluctuates into a $q\bar{q}$ pair and which subsequently interacts with the proton via a colour-neutral exchange, e.g. through a two-gluon ladder, and then hadronises into the vector meson. The $\psi(2S)$ and the $J/\psi(1S)$ have the same quark content, different radial distributions of the wave functions, and their mass difference is small compared to the HERA centre-of-mass energy. Therefore, the ratio of their electroproduction cross sections allows checking perturbative QCD predictions regarding their wave functions[1].

The luminosity used for this analysis was 468 pb^{-1} in total, which consists of data from 1996-2000 and 2002-2007 running periods (HERA I and HERA II, respectively). The kinematic range was $2 < Q^2 < 80$ GeV^2, $30 < W < 210$ GeV and $|t| < 1$ GeV^2. Events were selected with no activity in the central ZEUS detector in addition to signals from the scattered electron and the decay products of the studied mesons. The sample contained exclusive and a small fraction of proton-dissociative events with diffractive masses $M_Y < 4$ GeV which was assumed to cancel in the cross section ratio. The decay channels were: $J/\psi(1S), \psi(2S) \rightarrow \mu^+\mu^-$, and $\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^-$ with the subsequent decay $J/\psi(1S) \rightarrow \mu^+\mu^-$. The analysis was based on data collected with the ZEUS detector when 920(820) GeV protons collided with 27.5 GeV electrons or positrons. The DIFFVM [2] Monte Carlo (MC) was used for simulating the studied process. Exclusive and diffractive Bethe-Heitler dimuon production were simulated using the GRAPE package [3]. The results for the three cross-section

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ratios $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$: $R_{\mu\mu}$ for $\psi(2S) \to \mu^+\mu^-$, $R_{J/\psi\pi\pi}$ for $\psi(2S) \to J/\psi(1S)\pi^+\pi^-$ and $R_{\rm comb}$ for the combination, for the kinematic range $5 < Q^2 < 80\,{\rm GeV}^2$, $30 < W < 210\,{\rm GeV}$ and $|t| < 1\,{\rm GeV}^2$ and for the total integrated luminosity of 468 $\rm pb^{-1}$, are: $R_{J/\psi\pi\pi} = 0.26 \pm 0.03^{+0.01}_{-0.01}$, $R_{\mu\mu} = 0.24 \pm 0.05^{+0.02}_{-0.03}$, $R_{\rm comb} = 0.26 \pm 0.02^{+0.01}_{-0.01}$ and $R_{\psi(2S)} = 1.1 \pm 0.2^{+0.2}_{-0.1}$.

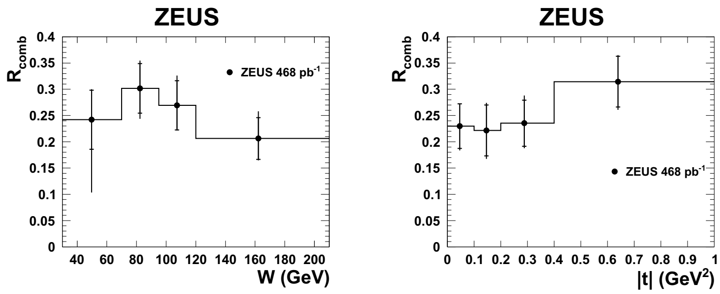

Figure 1. Cross-section ratio $R_{comb} = \sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ for the combined $psi(2S)$ decay modes as a function of W and $|t|$. The horizontal lines show the bin widths. The inner error bars show the statistical and the outer error bars show the quadratic sum of statistical and systematic uncertainties.

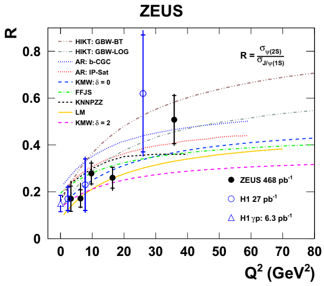

Figure 2. Comparison of the ZEUS measurement of the $R = \sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ ratio and the previous H1 results as a function of photon virtuality Q^2 together with theoretical predictions.

Fig. 1 shows the values of $R_{\rm comb}$ as a function of W and $|t|$ for $5 < Q^2 < 80\,{\rm GeV}^2$. In Fig. 2, the values of $R_{\rm comb}$ as a function of Q^2 are shown (including $2 < Q^2 < 5\,{\rm GeV}^2$ from the HERA I data) with H1 measurements [5]. The H1 collaboration has also measured $R = \sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ in photoproduction ($Q^2 \approx 0$), and found a value of $R = 0.150 \pm 0.035$ [4], which is consistent with the observed trend. The results are compared to model predictions from six different groups labelled: HIKT, KNNPZZ, AR, LP, FFJS and KMW. In order to calculate the exclusive production of vector charmonium states one has to determine: the probability of finding a $c\bar{c}$-dipole of transverse size r and impact parameter b in the photon in the infinite momentum frame; the $c\bar{c}$-dipole scattering amplitude or cross section of the proton as a function of r, b and $x_{\rm Bj} \approx (M_V + Q^2)/(W^2 + Q^2)$; the probability that the $c\bar{c}$-dipole forms the vector state V in the infinite momentum frame. The probability distribution of $c\bar{c}$-dipoles in the photon can be calculated in QED [6, 7]. For the probability that the $c\bar{c}$-dipole forms the vector state, its centre-of-mass wave function has to be boosted into the infinite momentum frame, which can be done using the boosted Gaussian model [8] calculations are used. All models predict a Q^2 dependent suppression of exclusive $\psi(2S)$ relative to $J/\psi(1S)$ production. For those, which explicitly use the wave functions of the vector mesons, this is caused by the node of the radial $\psi(2S)$ wave function, which leads to a destructive interference of the contributions to the production amplitude from small and large dipoles. Hüfner et al. [9] (HIKT) use two phenomenological parameterisations of the $c\bar{c}$-dipole cross section, GBW[10] and KST[11], which both describe the low-x inclusive DIS data from HERA. For the centre-of-mass wave functions of the $J/\psi(1S)$ and $\psi(2S)$, they use four different phenomenological potentials, BT, LOG, COR and POW, and c-quark masses between 1.48 and 1.84 GeV. However, only the models with c-quark masses around 1.5 GeV, GBW–BT and GBW–

LOG, are able to describe the cross sections of exclusive $J/\psi(1S)$ production measured at HERA. For the boost of the charmonium wave functions into the infinite momentum frame, they find the wave function from the Schrödinger equation and then boost the result. A major progress made [9] is the inclusion of the Melosh spin rotation into the boosting procedure, which enhances the $\psi(2S)$ to $J/\psi(1S)$ cross-section ratio by a factor of two to three. The model of Kopeliovich et al. [12–15] (KNNPZZ) uses the running gBFKL approach for the $c\bar{c}$-dipole cross section and the diffractive slope for its t dependence. The parameterisation of the $c\bar{c}$-dipole cross section used gives a quantitative description of the rise of the proton structure function at small x values as well as of the Q^2 and W dependence of diffractive $J/\psi(1S)$ production. KNNPZZ use parametrisations of the vector meson wave functions, inspired by the conventional spectroscopic models and short-distance behaviour driven by hard QCD gluon exchange. Armesto and Rezaeian [16] (AR) calculate the $c\bar{c}$-dipole cross section using the Impact-Parameter-dependent Color Glass Condensate model (b-CGC) [17] as well as the Saturation (IP-Sat) [18] dipole model, recently updated with fits to the HERA combined data [19, 20]. In the b-CGC model, which is restricted to the gluon sector, saturation is driven by the BFKL evolution, and its validity is therefore limited to $x_{\mathrm{Bj}} \lesssim 10^{-2}$. The IP-Sat model uses DGLAP evolution and smoothly matches the perturbative QCD limit at high values of Q^2. For the calculation of the light-cone $J/\psi(1S)$ and $\psi(2S)$ wave functions, the boosted Gaussian model and the leptonic decay widths $\Gamma_{ee}^{J/\psi(1S)}$ and $\Gamma_{ee}^{\psi(2S)}$ are used. Lappi and Mäntysaari [21, 22] (LM) use the BFKL evolution as well as the IP-Sat model to predict vector-meson production in ep and electron–ion collisions in the dipole picture. The wave functions of the $J/\psi(1S)$ and $\psi(2S)$ have been calculated according to the procedure developed previously [23, 24] and the low-x inclusive HERA data have been used to constrain the $c\bar{c}$-dipole cross section. Fazio et al. [25] (FFJS) use a two-component Pomeron model to predict the cross sections for vector-meson production. A normalisation factor of $f^{-1}_{\psi(2S)} = 0.45$ ensures that the value of the $\psi(2S)$ cross section is the same as for the other vector mesons at the same values of W, t and $Q^2_V = M^2_V + Q^2$ (i.e. $f_{\psi(2S)}\,\sigma_{\psi(2S)} = \sigma_{J/\psi}$). In this model the Q^2 dependence of the $\psi(2S)$ to $J/\psi(1S)$ suppression is caused by the difference of Q^2_V at a fixed Q^2 due to the $\psi(2S) - J/\psi(1S)$ mass difference. Kowalski, Motyka and Watt [23] (KMW) assume the universality of the production of vector quarkonia states in the scaling variable Q^2_V in their calculation of R. With the assumptions that the $c\bar{c} \to V$ transition is proportional to the leptonic decay width Γ^V_{ee} and that the interaction is mediated by two-gluon exchange and therefore proportional to $(\alpha_s(Q_V)\, x_{\mathrm{Bj}}\, g(x_{\mathrm{Bj}}, Q^2_V))^2$, R is given in the leading-logarithmic approximation [26–28] by

$$R = \left(\frac{\alpha_s(Q_{\psi(2S)})}{\alpha_s(Q_{J/\psi(1S)})}\right)^2 \frac{\Gamma_{\psi(2S)} M^{1-\delta}_{\psi(2S)}}{\Gamma_{J/\psi(1S)} M^{1-\delta}_{J/\psi(1S)}} \left(\frac{Q_{\psi(2S)}}{Q_{J/\psi(1S)}}\right)^{-6-4\bar{\lambda}+\delta} . \tag{1}$$

The running strong coupling constant, $\alpha_s(Q)$, and the gluon density, $g(x, Q^2)$, are evaluated at Q_V and x_{Bj}. For small x_{Bj} values, the gluon density can be parameterised as $x_{\mathrm{Bj}}\, g(x_{\mathrm{Bj}}, Q^2_V) \propto x_{\mathrm{Bj}}^{-\lambda(Q_V)}$ with $\lambda(Q_V) \simeq \bar{\lambda} = 0.25$ in the Q_V region of this measurement, while δ depends on the choice of the charmonium wave functions. For the non-relativistic wave functions $\delta = 0$ [26–28] and for the relativistic boosted Gaussian model $\delta \approx 2$ [23]. The Q^2 dependence of the ratio R in this approach is driven by kinematic factors and not by the form of the charmonia wave functions. All models predict only a weak W and $|t|$ dependence of R, as shown in Fig. 1. Therefore, only the comparison of the model calculations with the measurements as a function of Q^2 is presented in Fig. 2. All models predict an increase of R with Q^2, as observed in the data. The models are discussed below in the sequence from higher to lower predicted R values at high Q^2. From the HIKT calculations, the results for R for the two charmonium potentials BT and LOG with c-quark mass around 1.5 GeV and the GBW model for the $c\bar{c}$-dipole cross section are shown. The difference of the results when using the KST dipole cross sections are small. For Q^2 values below 24 GeV^2, the predicted R values for the

BT model are significantly larger than the measured values, whereas the values predicted by the LOG model agree with the data. For the AR calculations, the results for the b-CGC and IP-Sat models of the dipole cross sections are shown in the figure. For Q^2 values below 24 GeV^2, the b-CGC prediction for R is significantly higher than the data, whereas the IP-Sat model gives a good description of the data for the entire Q^2 range. The KMW model with $\delta = 0$ provides a good description of the observed Q^2 dependence of R, whereas the prediction for $\delta = 2$ is about 2 standard deviations below the R value measured for $Q^2 > 24$ GeV^2. The predictions of the models FFJS, KNNPZZ and LM also provide fair descriptions of the measurements. The material described above has recently been published [29].

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