

## 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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The exclusive deep inelastic electroproduction of  $\psi(2S)$  and  $J/\psi(1S)$  has been studied with the ZEUS detector at HERA in the kinematic range  $2 \leq Q^2 \leq 80 \text{ GeV}^2$ ,  $30 \leq W \leq 210 \text{ GeV}$ , and  $|t| \leq 1 \text{ GeV}^2$ , 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  $2 \leq Q^2 \leq 5 \text{ GeV}^2$  were taken in the HERA I running period and correspond to an integrated luminosity of  $114 \text{ pb}^{-1}$ . The data for  $5 \leq Q^2 \leq 80 \text{ GeV}^2$  are from both HERA I and HERA II periods and correspond to an integrated luminosity of  $468 \text{ pb}^{-1}$ . The decay modes analysed were  $\mu^+\mu^-$  and  $J/\psi(1S)\pi^+\pi^-$  for the  $\psi(2S)$  and  $\mu^+\mu^-$  for the  $J/\psi(1S)$  and the cross-section ratio  $\sigma(\psi(2S))/\sigma(J/\psi)$  has been measured as a function of  $Q^2$ ,  $W$  and  $t$ . The measurement is compared to predictions of QCD-inspired models of vector-meson production.

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## 1. Introduction

Exclusive electroproduction of vector mesons in deep inelastic scattering at high energies is usually described as a multi-step process: the electron emits a virtual photon,  $\gamma^*$ , with virtuality  $Q^2$  and  $\gamma^*p$  centre-of-mass energy  $W$ , in leading order QCD the  $\gamma^*$  fluctuates into a  $q\bar{q}$  pair with a lifetime which, at large values of  $W$ , is long compared to the  $\gamma^*p$  interaction time, and the  $q\bar{q}$  pair interacts with the proton with momentum transfer squared  $t$  via a colour-neutral exchange, e.g. through a two-gluon ladder, and then hadronizes into the vector meson  $V$ . As  $J/\psi(1S)$  and  $\psi(2S)$  have the same quark content, similar masses but different wave-functions, the ratio of their deep-inelastic exclusive production cross-sections allows the checking of perturbative QCD predictions of the wave-function dependence of exclusive virtual vector-meson production [1].

The luminosity used for this analysis is  $468 \text{ pb}^{-1}$ , which consists of data coming from the 1996–2000 and 2002–2007 HERA run periods, which are commonly referred to as “HERA I” and “HERA II”, respectively, which correspond to integrated luminosities of  $114 \text{ pb}^{-1}$  and  $354 \text{ pb}^{-1}$ . The kinematic range for the virtuality is  $5 \leq Q^2 \leq 80 \text{ GeV}^2$ , for the centre-of mass energy of the virtual-photon proton system  $30 \leq W \leq 210 \text{ GeV}$ , and for the absolute value of the momentum transfer to the proton  $|t| \leq 1 \text{ GeV}^2$ . A sub-sample of  $114 \text{ pb}^{-1}$  of HERA I data was used for an extra measurement for  $2 \leq Q^2 \leq 5 \text{ GeV}^2$ . Events are selected with no activity in the central ZEUS detector in addition to signals from the scattered electron and the decay products of the  $\psi(2S)$  or  $J/\psi(1S)$ . Thus the event sample contains both exclusive and a small fraction of proton-diffractive events, with diffractive masses  $M_Y \lesssim 4 \text{ GeV}$ . We assume that this background essentially cancels in the  $\psi(2S)$  to  $J/\psi(1S)$  ratio. The decay channels used were  $J/\psi(1S) \rightarrow \mu^+\mu^-$ ,  $\psi(2S) \rightarrow \mu^+\mu^-$  and  $\psi(2S) \rightarrow J/\psi(1S) \pi^+\pi^-$  with the subsequent decay  $J/\psi(1S) \rightarrow \mu^+\mu^-$ .

## 2. Event selection and extraction of the signal

The measurement was based on data collected with the ZEUS detector at the HERA collider when 920 (820) GeV protons collided with 27.5 GeV electrons or positrons. The sample used for this study corresponds to an integrated luminosity of  $38 \text{ pb}^{-1}$  and  $430 \text{ pb}^{-1}$  for  $ep$  centre-of-mass energies 300 GeV and 318 GeV, respectively. The luminosity-weighted  $ep$  centre-of-mass energy is 317 GeV.

The DIFFVM [2] Monte Carlo (MC) was used for simulating exclusive vector meson production,  $ep \rightarrow eVp$ , where  $V$  denotes the produced vector meson. Exclusive and diffractive dimuon production (Bethe-Heitler background) were simulated using the electroweak dimuon simulator GRAPE [3].

Measured and simulated samples were analysed with the same reconstruction and analysis software.

The online event selection required an electron candidate in the rear part of the ZEUS calorimeter (CAL), which surrounds the beam pipe in the electron-beam direction. The central tracking detector (CTD) and the microvertex detector (MVD) were used to reconstruct the momentum vectors of the charged decay products of  $J/\psi(1S)$  and  $\psi(2S)$ . In order to select deep-inelastic events, at least one electron candidate with an energy  $E_e > 10 \text{ GeV}$  and an electron probability greater than 90% as reconstructed by the SINISTRA algorithm [4] was required. The position of the scattered electron was required to be outside of areas with significant inactive material in front of

**Table 1:** Cross-section ratio  $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$  for the  $\psi(2S)$  decay modes  $\mu^+\mu^-$ ,  $J/\psi(1S)\pi^+\pi^-$ , and their combination for the kinematic range  $5 \leq Q^2 \leq 80 \text{ GeV}^2$ ,  $30 \leq W \leq 210 \text{ GeV}$ , and  $|t| \leq 1 \text{ GeV}^2$  using both HERA I and HERA II data.

$\psi(2S)$ decay mode	$\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$
$J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$	$0.26 \pm 0.03^{+0.01}_{-0.01}$
$\mu^+\mu^-$	$0.24 \pm 0.05^{+0.02}_{-0.03}$
combined	$0.26 \pm 0.02^{+0.01}_{-0.01}$

the calorimeter. To select events with exclusively produced  $J/\psi(1S)$  or  $\psi(2S)$  vector mesons, the following further requirements were imposed:

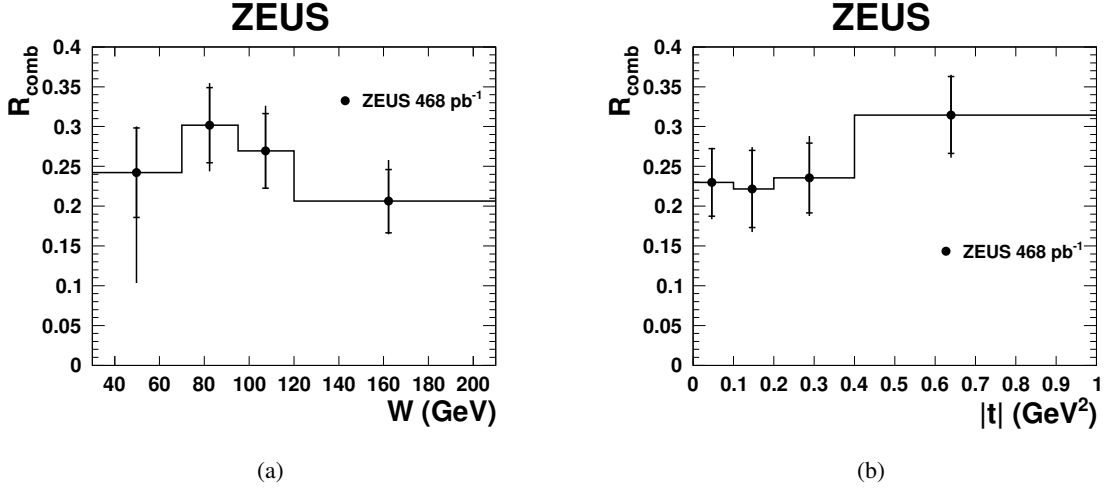
- The  $Z$  coordinate of the interaction vertex along the beam direction was required to be within  $\pm 30 \text{ cm}$  of the nominal interaction point.
- In addition to the scattered electron, the presence of two oppositely charged muons, and for  $\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^-$ , additionally two oppositely charged pions, were required.
- Events with calorimeter islands with energies above  $0.4 \text{ GeV}$  (excluding electron candidates outside of the tracking acceptance) not matched to the tracks were rejected.
- The presence of a positive and a negative muon was required. Muons were identified using the GMUON algorithm [5] with muon quality  $\geq 1$ .
- For selecting  $\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^-$  candidates, the transverse momentum of each pion was required to exceed  $0.12 \text{ GeV}$ .

The number of events obtained after applying the selection criteria and after background subtraction for the region  $5 < Q^2 < 80 \text{ GeV}^2$  are 2224, 97 and 80 for the  $J/\psi(1S) \rightarrow \mu^+\mu^-$ ,  $\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^-$  and  $\psi(2S) \rightarrow \mu^+\mu^-$  decays, respectively. For  $2 < Q^2 < 5 \text{ GeV}^2$ , the number of events are 297, 11 and 4.

### 3. Results

The results for the three cross-section ratios  $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$ ,  $R_{\mu\mu}$  for  $\psi(2S) \rightarrow \mu^+\mu^-$ ,  $R_{J/\psi\pi\pi}$  for  $\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^-$ , and  $R$  for the combined branching fractions, are reported in Table 1 for the kinematic range  $5 \leq Q^2 \leq 80 \text{ GeV}^2$ ,  $30 \leq W \leq 210 \text{ GeV}$ , and  $|t| \leq 1 \text{ GeV}^2$ . For the  $J/\psi(1S)$  the  $\mu^+\mu^-$  decay mode was used.

Fig. 1(a) and Fig. 1(b) show the  $W$  and  $|t|$  dependencies of  $R$  from the HERA II data, and Fig. 2 shows its  $Q^2$  dependence. The extra bin  $2 < Q^2 < 5 \text{ GeV}^2$ , from the HERA I data is also shown. The production ratio shows a tendency to rise as a function of  $Q^2$ . The data are also compared to the previous H1 measurement [6]. The results are compatible. Due to the higher integrated luminosity, the ZEUS measurement is significantly more precise. In photoproduction ( $Q^2 \sim 0$ ), H1 measured a value [7] of  $R = 0.150 \pm 0.035$ , consistent with the trend as a function  $Q^2$  observed here in DIS.



**Figure 1:** Cross-section ratio  $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$  for the combined  $\psi(2S)$  decay modes as function of (a) the photon-proton centre-of-mass energy  $W$ , and (b) the square of momentum transfer to the proton  $t$ . The horizontal error bars show the bin widths, the inner vertical error bars the statistical and the outer error bars the quadratic sum of statistical and systematic uncertainties.

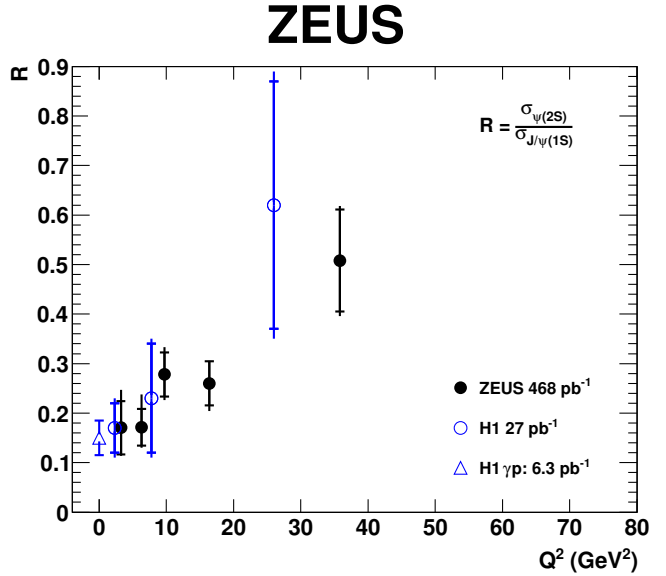
As cross check it has been verified that the ratio  $R_{\mu\mu}$  to  $R_{J/\psi\pi\pi}$  is compatible with 1. For the entire kinematic range of the measurement a value of  $R_{\mu\mu}/R_{J/\psi\pi\pi} = 1.1 \pm 0.2^{+0.2}_{-0.1} \pm 0.1$ , is found. The first error is the statistical uncertainty, the second the systematic uncertainty of the measurement and the third the uncertainty of the  $\psi(2S)$  branching fractions.

#### 4. Comparison to model prediction

Several models predict the cross-section ratio of  $\psi(2S)$  to  $J/\psi(1S)$  vector meson production in exclusive deep inelastic scattering. Models from six different groups are briefly described here and compared to the data, as shown in Fig. 3.

A model from Nemchik et al. [8, 9] (KNNPZZ) was used to compare to the previous H1 measurement. This model describes the BFKL pomeron in terms of the colour-dipole cross section which is a solution of the generalised BFKL equations. The suppression of the  $\psi(2S)$  cross section relative to the  $J/\psi(1S)$  cross section occurs because the  $\psi(2S)$  wave-function has a radial node close to the dipole radius, which causes cancellations in the production amplitudes.

In a calculation by Armesto and Rezaeian [10] (AR), the wave-functions of the vector mesons were determined via a fit to the leptonic decay data. Two predictions are considered: results from



**Figure 2:** Comparison of the ZEUS measurement of  $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$  to the previous H1 measurements as function of photon virtuality  $Q^2$ .

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the Impact-Parameter dependent Color Glass Condensate (b-CGC) and the Saturation (IP-Sat) dipole models. The predictions are given at  $W = 120$  GeV. The b-CGC/IP-Sat predictions for  $R$  are then the corresponding band between these two curves which include also uncertainties coming from the choice of charm mass within  $1.27 - 1.4$  GeV in both models.

An effective description of exclusive vector meson productions follows from the assumption of universality of the production mechanism of various quarkonia species, combined with the QCD description of quarkonia production in the leading logarithmic approximation [11]. The  $\psi(2S)$  to  $J/\psi$  cross-section ratio was calculated by Kowalski et al. [12] for a non-relativistic meson wave-function (KMW  $\delta = 0$ ), and for a relativistic "boosted Gaussian" wave-functions (KMW  $\delta = 2$ ).

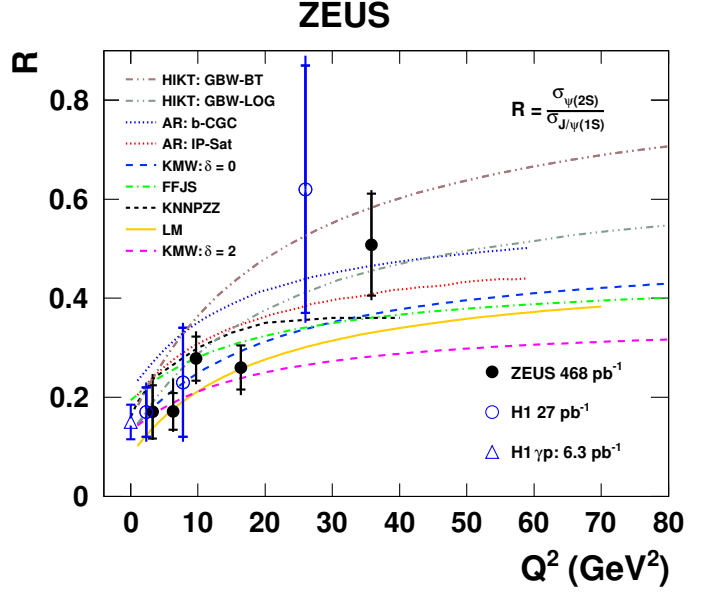
A prediction from Fazio et al. [13] (FFJS) uses a two component Pomeron model to predict the cross sections for vector meson production. A normalisation factor of  $f_{\psi(2S)}^{-1} = 0.45$  ensures that the  $\psi(2S)$  cross section is the same as for other vector mesons at a given value of  $W$ ,  $t$  and  $Q^2 + M_V^2$  (i.e.  $f_{\psi(2S)}\sigma_{\psi(2S)} = \sigma_{J/\psi}$ ).

A prediction from Lappi and Mäntysaari [14] (LM) in the dipole picture using the IP-Sat model is used to predict vector meson production in  $ep$  and electron-ion collisions. Low- $x$  inclusive HERA data has been used to constrain the dipole cross section. The wave-functions for  $J/\psi$  and  $\psi(2S)$  are orthogonal and calculated according to a procedure developed previously [12]. The predictions are given at  $W = 120$  GeV.

A prediction from Hüfner et al. [15] (HIKT) also uses the dipole model to predict vector meson production. The dipole-proton interaction cross section is constrained by the inclusive deep inelastic scattering data from HERA. The main theoretical challenge is the procedure of Lorentz boosting the charmonium wave function, which is known only in the charmonium rest frame as a solution of the Schrödinger equation with available realistic potentials ("BT" and "LOG").

## 5. Summary

The cross-section ratio of  $\sigma_{\psi(2S)}/\sigma_{J/\psi(1S)}$  in exclusive electroproduction in the kinematic range  $2 \leq Q^2 \leq 80$  GeV<sup>2</sup>,  $30 \leq W \leq 210$  GeV, and  $|t| \leq 1$  GeV<sup>2</sup> at an electron-proton center-of-mass energy of 317 GeV has been measured with data corresponding to a luminosity of 468 pb<sup>-1</sup> recorded by the ZEUS experiment at HERA. The decay channels used 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 has been determined as a func-



**Figure 3:** Comparison of the ZEUS  $R$  measurement to the previous H1 results as function of photon virtuality  $Q^2$  together with theoretical predictions

tion of  $Q^2$ ,  $W$  and  $|t|$ . Thanks to the increased luminosity the measurement is significantly more precise than the previous measurement by the H1 collaboration, which has used early HERA data. Various predictions are independent of  $W$  and  $|t|$  within the uncertainties of the measurement for the cross-section ratio, but show a tendency to increase with  $Q^2$ . Some discrimination of the different models is possible, although a large spread in the predictions indicates that the uncertainty on the theory is large.

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