PROCEEDINGS OF SCIENCE

PoS(DIS2014)187

Charmonium production at HERA

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The exclusive deep-inelastic electro-production of $\psi(2S)$ and $J/\psi(1S)$ has been studied with the ZEUS detector at HERA using data corresponding to an integrated luminosity of $354\,\text{pb}^{-1}$. The decay modes analyzed were $\mu^+\mu^-$ and $J/\psi(1S)\,\pi^+\pi^-$ for the $\psi(2S)$, and $\mu^+\mu^-$ for the $J/\psi(1S)$. The analysis was carried out in the kinematic range $5 \leq Q^2 \leq 70\,\text{GeV}^2$, $30 \leq W \leq 210\,\text{GeV}$, and $|t| \leq 1\,\text{GeV}^2$, where Q^2 is the photon virtuality, W the virtual-photon proton centre-of-mass energy, and t the squared four-momentum transfer at the proton vertex. The cross-section ratio $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ has been measured as a function of Q^2, W and t.

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects,
28 April - 2 May 2014
Warsaw, Poland

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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, γ^*, with virtuality Q^2 and $\gamma^* p$ centre-of-mass energy W, in leading order QCD the γ^* 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 checking perturbative QCD predictions of the wave-function dependence of exclusive virtual vector-meson production [1].

At HERA deep-inelastic exclusive $J/\psi(1S)$ electroproduction has been measured for $2 < Q^2 < 100\,\mathrm{GeV}^2$, $30 < W < 220\,\mathrm{GeV}$ and $t < |1|\,\mathrm{GeV}^2$ by the experiment ZEUS [2] and for $2 < Q^2 < 80\,\mathrm{GeV}^2$, $25 < W < 180\,\mathrm{GeV}$ and $|t| < 1.6\,\mathrm{GeV}^2$ by the experiment H1 [3]. The H1 collaboration also measured diffractive $\psi(2S)$ production in the reaction $\gamma^* p \to \psi(2S) + Y$, where Y denotes either a proton or a low-mass proton-dissociation system [3]. The decay channels used were $\psi(2S) \to \mu^+\mu^-$ and e^+e^-, and $\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-$ with the decay $J/\psi(1S) \to \mu^+\mu^-$ and e^+e^-.

The luminosity used for this analysis is $354\,\mathrm{pb}^{-1}$, and the kinematic range for the virtuality $5 \leq Q^2 \leq 70\,\mathrm{GeV}^2$, for the centre-of mass energy of the virtual-photon proton system $30 \leq W \leq 210\,\mathrm{GeV}$, and for the absolute value of the momentum transfer to the proton $|t| \leq 1\,\mathrm{GeV}^2$. 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 $M_Y \lesssim 4\,\mathrm{GeV}$. We assume that this background essentially cancels in the $\psi(2S)$ to $J/\psi(1S)$ ratio.

2. Event selection and extraction of the signal

The measurement is based on data collected with the ZEUS detector at the HERA collider when 920 GeV protons collided with 27.5 GeV electrons or positrons. The sample used for this study corresponds to an integrated luminosity of $354\,\mathrm{pb}^{-1}$.

The DIFFVM [4] Monte Carlo (MC) was used for simulating exclusive vector meson production, $ep \to eVp$, where V denotes the produced vector meson. For the event generation the following parametrisations were used: for the dependence on photon virtuality Q^2 the square of the V propagator $(1 + Q^2/M_V^2)^{-1.5}$ and $(Q/M_V)^2$ for the ratio of longitudinal to transverse virtual γ^* cross-section, for the dependence on t, the momentum transfer squared to the proton $\exp(bt)$, with $b = 4\,\mathrm{GeV}^2$, SCHC (s-channel helicity conservation) for the decays $V \to \mu^+\mu^-$, and a flat angular distribution for the $\psi(2S) \to J/\psi(1S)\pi^+\pi^-$ decay.

Exclusive and diffractive dimuon production (Bethe-Heitler background) were simulated using the electroweak dimuon simulator GRAPE [5].

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. In order to select deep-inelastic events, at least one electron candidate with an energy $E_e > 10\,\mathrm{GeV}$ and an electron probability greater than 90 % as reconstructed by the SINISTRA algorithm [6] was required. The position of the scattered electron was required to be outside of areas with significant inactive material in front of the calorimeter.

In the kinematic range of the analysis, charged particles were tracked in the central tracking detector (CTD) and the microvertex detector (MVD). 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 ±30 cm of the nominal interaction point.
- In addition to the scattered electron, the presence of two oppositely charged muons, and for $\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-$, additionally two oppositely charged pions, was required. The tracks had to satisfy following criteria: each track had to cross at least 3 CTD super-layers with the hit closest to beam in the first CTD super-layer or in the MVD.
- Events with calorimeter islands with energies above 0.4 GeV (excluding electron candidates outside of the tracking acceptance) not matched to the tracks were rejected. The threshold value of this cut was optimized between minimizing the loss of events and maximizing the rejection of non-exclusive vector-meson production with additional energy deposits in the CAL.
- The presence of a positive and a negative muon was required. Muons were identified using the GMUON algorithm [7] with muon quality ≥ 1.
- For selecting $\psi(2S) \to J/\psi(1S)\,\pi^+\pi^-$ candidates, the transverse momentum of each pion was required to exceed 0.12 GeV.

Fig. 1 shows the $\mu^+\mu^-$ effective mass distribution in logarithmic scale for the selected events. The solid line shown is the fit of a straight line to the sidebands of the signals: $2.0 < M_{\mu\mu} < 2.62\,\mathrm{GeV}$, and $4.05 < M_{\mu\mu} < 5.0\,\mathrm{GeV}$. The ratio of $\psi(2S)$ to $J/\psi(1S)$ events was obtained from the ratio of the number of events above the straight-line background in the range $3.59 < M_{\mu\mu} < 3.79\,\mathrm{GeV}$ to the corresponding number for the range $3.02 < M_{\mu\mu} < 3.17\,\mathrm{GeV}$. According to a detailed Monte Carlo study this choice minimizes the systematic uncertainty due to the uncertainties of the mass resolution and the

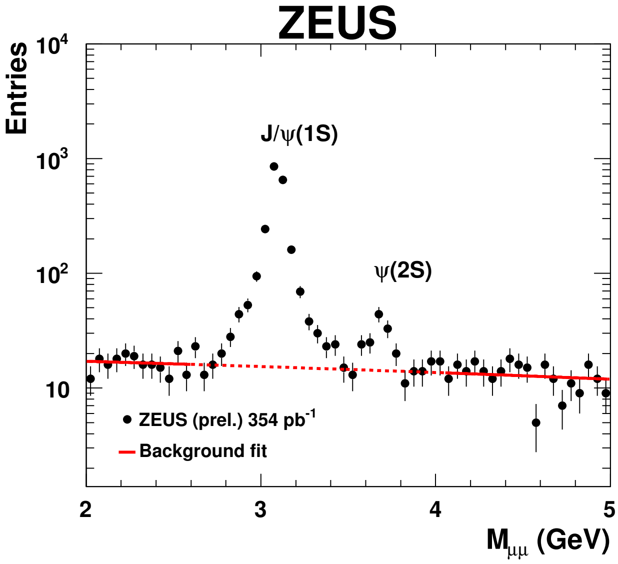


Figure 1: Two-muon invariant-mass distribution, $M_{\mu\mu}$, in logarithmic scale. The dots with error bars are the data, the solid line a linear fit to the background outside of the $J/\psi(1S)$ and $\psi(2S)$ signal region.

shape of the background. The difference in widths of the mass bins chosen takes into account the worsening of the mass resolution with increasing $M_{\mu\mu}$.

We note that also the Bethe-Heitler Monte Carlo events provide a good description of the background shape, and that the absolute normalisation agrees within the estimated uncertainty of about 20 %.

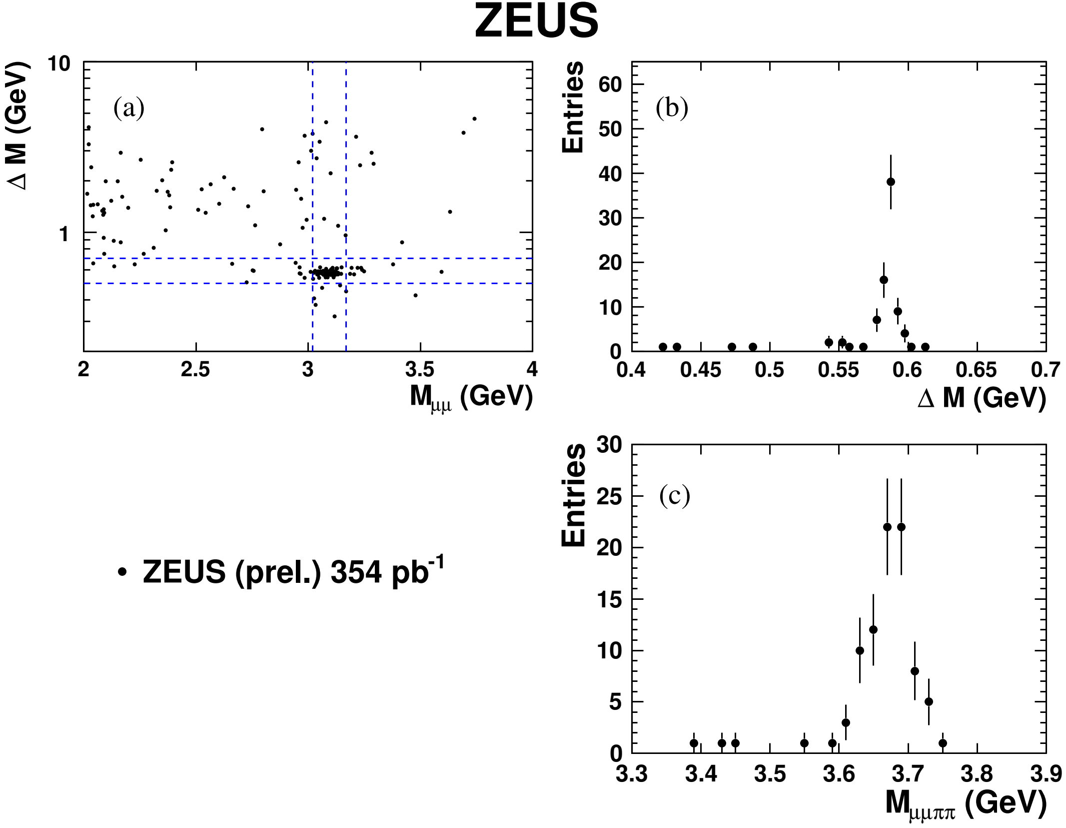


Figure 2: a) Scatter plot $M_{\mu\mu}$ versus $\Delta M = M_{\mu\mu\pi\pi} - M_{\mu\mu}$, b) ΔM distribution for $3.02 < M_{\mu\mu}(\mathrm{GeV}) < 3.17$, and c) $M_{\mu\mu\pi\pi}$ distribution for $3.02 < M_{\mu\mu}(\mathrm{GeV}) < 3.17$.

Fig. 2 shows for the $\mu\mu\pi\pi$ events a scatter plot $M_{\mu\mu}$ versus $\Delta M = M_{\mu\mu\pi\pi} - M_{\mu\mu}$, the ΔM distribution for $3.02 < M_{\mu\mu} < 3.17$ GeV, and the $M_{\mu\mu\pi\pi}$ distribution for $3.02 < M_{\mu\mu} < 3.17$ GeV. As expected the ΔM distribution shows a narrow peak at the nominal $\psi(2S) - J/\psi(1S)$ mass difference of 589.2 MeV. For the ratio of $\psi(2S)$ to $J/\psi(1S)$ events the cuts $3.02 < M_{\mu\mu} < 3.17$ GeV and $0.5 < \Delta M < 0.7$ GeV were chosen. As can be seen from Fig. 2, there is hardly any background below the $\psi(2S)$ signal. An upper limit of 3 events has been estimated for the background.

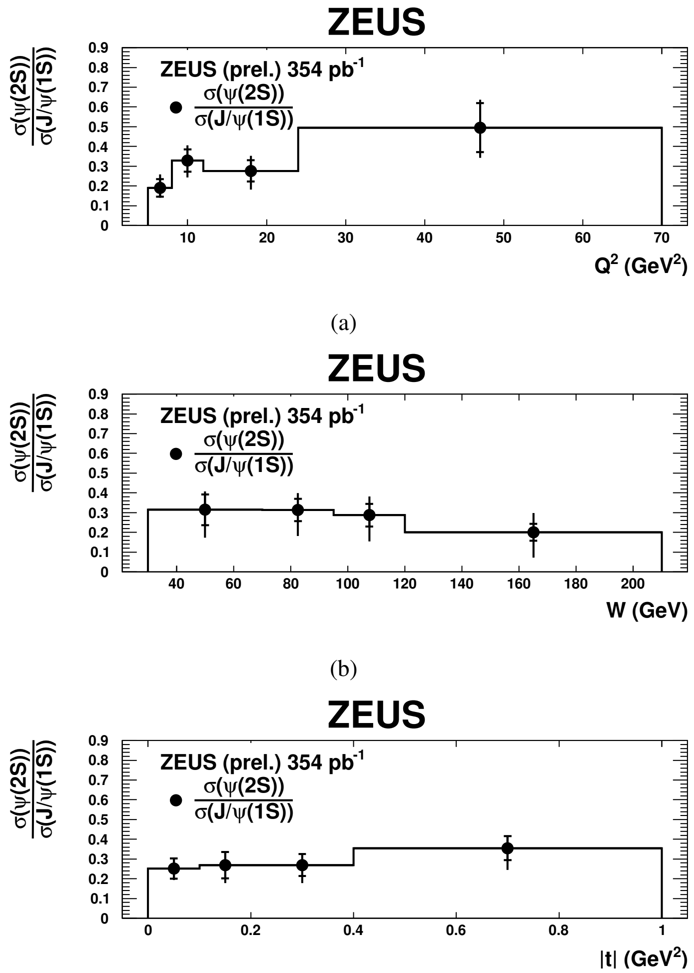
3. Results

The results for the three cross-section 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_{comb} for the combined branching fractions, are reported in Table 1 for the entire kinematic range $5 \leq Q^2 \leq 70\,\mathrm{GeV}^2$, $30 \leq W \leq 210$ GeV, and $|t| \leq 1\,\mathrm{GeV}^2$.

For the $J/\psi(1S)$ the $\mu^+\mu^-$ decay mode was used. Fig. 3(a), Fig. 3(b) and Fig. 3(c) show the Q^2, W and $|t|$ dependencies of $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ for the combined $\psi(2S)$ decay modes.

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 $5 \leq Q^2 \leq 70\,\mathrm{GeV}^2$, $30 \leq W \leq 210\,\mathrm{GeV}$, and $|t| \leq 1\,\mathrm{GeV}^2$.

$\psi(2S)$ decay mode	$\sigma(\psi(2S))/\sigma(J/\psi(1S))$
$J/\psi(\rightarrow \mu^+\mu^-)\pi^+\pi^-$	$0.29 \pm 0.04^{+0.02}_{-0.01}$
$\mu^+\mu^-$	$0.25 \pm 0.05^{+0.04}_{-0.02}$
combined	$0.28 \pm 0.03^{+0.02}_{-0.01}$



(a)

(b)

(c)

Figure 3: Cross-section ratio $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ for the combined $\psi(2S)$ decay modes as function of (a) photon virtuality Q^2, (b) the photon-proton centre-of-mass energy W, and (c) 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.

Fig. 4 shows the comparison of the ZEUS measurements to the H1 measurements. In the common kinematic regions the same bin width for the ZEUS analysis was chosen. Both measurements are compatible. Thanks to the higher integrated luminosity the precision of the ZEUS measurements is significantly increased.

As cross check it has been verified that the ratio $R_{\mu\mu}$ to $R_{J/\psi\pi\pi}$ is compatible with 1. We find $R_{\mu\mu}/R_{J/\psi\pi\pi} = 1.16 \pm 0.28^{+0.14}_{-0.14}$, where the first error is the statistical and the second the systematic uncertainty. The errors do not include the uncertainties of the branching fractions.

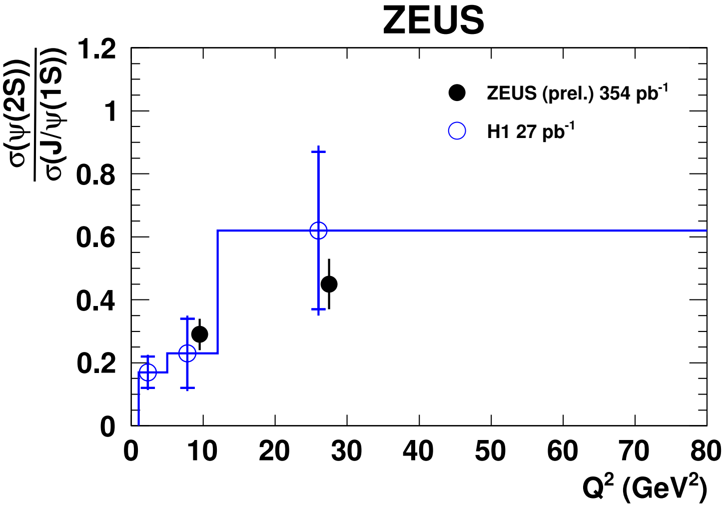


Figure 4: Top: Comparison of the ZEUS measurement of $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ to the previous H1 measurement as function of photon virtuality Q^2.

4. Summary

The cross-section ratio of $\sigma(\psi(2S))/\sigma(J/\psi(1S))$ in exclusive electroproduction in the kinematic range $5 \leq Q^2 \leq 70\,\mathrm{GeV}^2$, $30 \leq W \leq 210\,\mathrm{GeV}$, and $|t| \leq 1\,\mathrm{GeV}^2$ at an electron-proton center-of-mass energy of 318 GeV has been measured with data corresponding to a luminosity of $354\,\mathrm{pb}^{-1}$ 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 function of Q^2, W and $|t|$. The measurement is significantly more precise than the previous measurement by the H1 collaboration, which has used early HERA data.

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