Charmonium Production in *ep* Collisions at HERA[1]

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Abstract

New results are presented on the production of J/ψ mesons in electron proton collisions, measured with the ZEUS and H1 detectors at HERA. The J/ψ mesons are detected by their leptonic decay modes into electrons and muons. The results on inelastic J/ψ production are interpreted in the framework of the colour singlet model while elastic J/ψ production is compared with diffractive models based on pomeron exchange. The photoproduction cross section for elastic J/ψ meson production is observed to rise with the center-of-mass energy, faster than expected from the exchange of a soft pomeron. The energy dependence of the cross section for inelastic production agrees in shape with the NLO QCD calculations based on the colour singlet model, if the gluon distribution in the proton is assumed to rise strongly towards low x.

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1 Introduction

The study of heavy quark production provides important information about the dynamics of particle interactions [1]. The production of heavy quarkonia, like J/ψ, $\psi\prime$, Υ, has been studied in e^+e^- annihilation, hadronic collisions, deep inelastic lepton nucleon scattering, and photoproduction experiments, covering a large range of center-of-mass energies. At HERA, the electron beam can be viewed as an intense source of almost real photons *(photoproduction, $Q^2 \approx 0$)*. The contribution of events where the scattered electron is seen in the main detector *(deep inelastic scattering, $Q^2 > 4\,\mathrm{GeV}^2$)*, is found to be smaller than in *photoproduction*.

The mechanisms that are commonly used to describe the photoproduction of J/ψ mesons are depicted in fig. 1. The inelastic production of J/ψ mesons is described by the *photon-gluon fusion* process and consecutive emission of a gluon to produce a colour singlet final state *(colour singlet model,* fig. 1a) [2]. Recently, next-to-leading order and relativistic corrections to the colour-singlet model have been calculated [3, 4]. In the *Vector Meson Dominance* model (VDM) [5], the J/ψ mesons are produced by a diffractive mechanism, based on *pomeron* exchange (fig. 1b). The proton is either remaining intact (as shown) or dissociating. Recently attempts have been made to replace the pomeron by a gluon ladder within QCD inspired diffractive models (fig. 1c) [6]. Vector meson production ($\rho, \omega, \Phi, J/\psi$) can therefore be used as a probe of the soft pomeron and perturbative QCD (hard) regimes in strong interactions.

In the perturbative QCD models, both elastic and inelastic J/ψ cross sections strongly depend on the behaviour of the gluon density distribution of the proton at low x_g (already in leading order). Heavy quark production therefore offers the possibility to probe the gluon distribution either, indirectly, by measuring the production cross section, or directly, by explicit reconstruction of x_g, the momentum fraction of the proton carried by the gluon.

2 Kinematics

The experiments described here, were carried out using the ZEUS [7] and H1 [8] detectors at the HERA storage ring at DESY. The data were collected during the 1993 (1994) running periods where 26.7 GeV electrons (27.5 GeV positrons) were collided with 820 GeV protons, at a center of mass energy of about 300 GeV. The electron proton scattering process

$$e(l) + p(p) \to e(l') + J/\psi(p_\psi) + X(p_X), \tag{1}$$

where the quantities in parentheses denote the particles' four-momenta, is described by the usual deep inelastic scattering variables

$$s = (l+p)^2 \approx 10^5\,\mathrm{GeV}^2; \qquad Q^2 = -q^2 \le 10^5\,\mathrm{GeV}^2; \qquad y = \frac{qp}{lp}\left[= \frac{E_\gamma}{E_e}\right]. \tag{2}$$

Here $q = l - l'$ represents the four-momentum of the exchanged photon and the last equation holds in the proton rest frame.

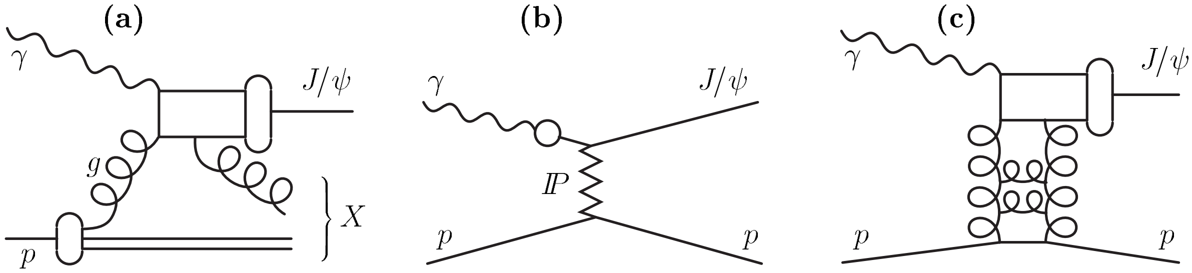

Figure 1: J/ψ production mechanisms: (a) inelastic J/ψ production via photon gluon fusion, (b) elastic J/ψ production via pomeron exchange, (c) elastic J/ψ production in QCD inspired diffractive models.

The electroproduction cross section can be represented as a convolution of the flux of photons emitted by the electron with the photoproduction cross section ($Q^2 \approx 0$, *Weizsäcker-Williams Approximation)* [9]

$$\sigma(ep \to c\bar{c}X) = \int dy f_{\gamma/e}(y)\sigma(\gamma p \to c\bar{c}X). \qquad (3)$$

The photoproduction process, in turn, is described by

$$s_{\gamma p} = W_{\gamma p}^2 = (p+q)^2 \approx 4E_e E_p y; \qquad z = \frac{pp_\psi}{pq} = \left[\frac{E_\psi}{E_\gamma}\right]. \qquad (4)$$

The inelasticity z is commonly used to distinguish the *pure elastic* ($\gamma p \to J/\psi\, p$), *proton dissociative* ($\gamma p \to J/\psi\, X$), and *inelastic* ($\gamma p \to J/\psi X$) contributions to the production process. In particular, the separation of the diffractive process is experimentally difficult because the proton fragments disappear in the beam pipe, and these events look like elastic events.

The J/ψ mesons are identified by their decays into lepton pairs (electrons or muons). Electrons are detected in the electromagnetic part of the calorimeters by linking a driftchamber track to a calorimeter cluster and demanding the measured energy to be comparable to the measured momentum. Tracks are identified as muons if they are linked to track elements reconstructed in the muon detectors. Muons are also identified as minimum ionizing particles in the calorimeter, thus extending the analysis to lower lepton momentum.

3 Elastic photoproduction of J/ψ mesons

Candidate events for elastic photoproduction of J/ψ mesons are selected by demanding exactly two particles identified as a pair of either electrons or muons in the detector. No further hadronic activity is allowed in the forward[2] region of the detectors. Clear signals are observed in the mass distributions, as shown in fig. 2a for the case $J/\psi \to e^+e^-$ measured by the ZEUS collaboration. The asymmetric shape of the mass peak in fig. 2a is attributed to the decay electrons loosing part of their energy due to bremsstrahlung. The background can be well described by lepton pairs produced in the two-photon process $\gamma\gamma \to e^+e^-, \mu^+\mu^-$, where both the electron and the proton radiate a photon (shaded area in fig. 2a). In the case of the ZEUS analysis of the electron decay mode, about half of the background is attributed to pion misidentification, represented by the difference between the dashed line and the shaded area in fig. 2a.

The contribution from proton dissociative production is estimated using the forward part of the detectors, e.g. by looking for events with an energy deposit in the calorimeters at polar angles below 10 degrees. The cross section measurements are corrected for this contaminations which is $(17^{+8}_{-10} \pm 10)$ % in the ZEUS 1993 data analysis and (21 ± 5) % in the H1 analysis.

The ep cross section is converted into a γp cross section using eq. (3). The γp cross section for elastic J/ψ production is presented as a function of the photon-proton center-of-mass energy, $W_{\gamma p}$ in fig. 3 in comparison with measurements at fixed-target experiments at lower energies [10] and various theoretical predictions. The ZEUS measurement has recently been published [11]. A significant rise of the cross section is observed as a function of $W_{\gamma p}$, both with respect to low energy measurements and in the HERA data alone. The rise cannot be accounted for by soft pomeron models [12] (dashed line in fig. 3, normalized to the E516 point) which predict a milder dependence of the form

$$\sigma_{el} \sim W_{\gamma p}^{4\varepsilon} \qquad \text{with} \quad \varepsilon \approx 0.08 \qquad (5)$$

[2]Both H1 and ZEUS are using a right-handed coordinate system with the z axis pointing into the direction of the proton beam (forward), the x axis pointing towards the center of the storage ring, and the y axis pointing upward. The direction of the incoming electron beam is termed backward. The polar angle θ is measured with respect to the proton direction.

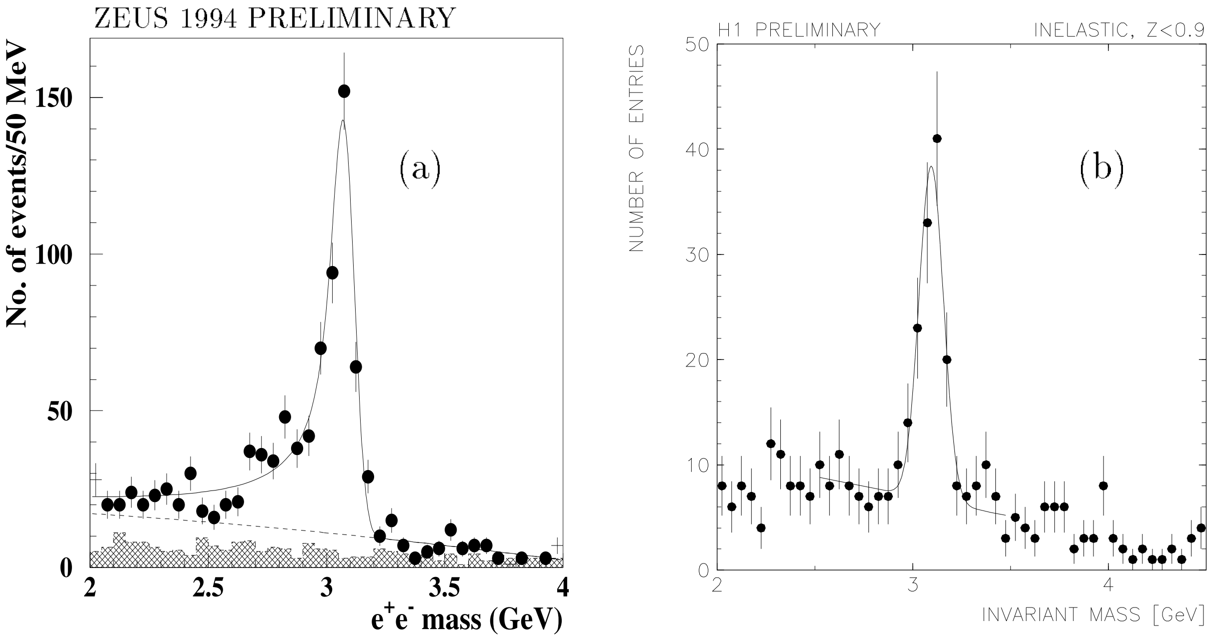

Figure 2: (a) Invariant mass distribution for elastic $J/\psi \to e^+e^-$ production as measured by the ZEUS collaboration (1994 data). The solid circles represent the data, the shaded area is the expected contribution due to the two photon background. The dashed line represents the total background. The solid line indicates a fit to the data with a Gaussian convoluted with a bremsstrahlung function and a quadratic polynomial parametrizing the background. (b) Invariant mass distribution for inelastic $J/\psi \to \mu^+\mu^-$ candidates as measured by the H1 experiment (1994 data). The points represent the data. The solid line indicates a fit to the data with a Gaussian plus a linear term to describe the background.

as seen in hadroproduction [13]. The rise can, however, be well reproduced by a $W_{\gamma p}$ dependence as in eq. (5), but with $\varepsilon \approx 0.2 \div 0.25$. Recent QCD inspired models [6] predict a cross section dependence on the gluon density distribution in the proton, according to

$$\sigma_{el} \sim [xg(x)]^2 \left[F_N^{2G}\right]^2 \tag{6}$$

These models are able to describe the data if the gluon density is assumed to rise at low x (high $W_{\gamma p}$). The second term accounts for (a priori unknown) non-perturbative effects in the two-gluon interaction. Using the upper and lower limit of the gluon momentum distribution as determined by the ZEUS experiment [14], this model predicts the band spanned by the two dashed-dotted lines in fig. 3.

Only a moderate increase as a function of $W_{\gamma p}$ is observed for the total photoproduction cross section and the ρ, ω, and Φ photoproduction cross sections, in impressive agreement with the soft pomeron prediction. Therefore the transition from the soft pomeron description, which is adequate in the case of light vector mesons, to a perturbative QCD description, which seems to describe J/ψ production better, can be probed by comparing light and heavy vector meson production at HERA. It is worth noting that besides the heavy quark mass, another large scale is involved in ep scattering, namely the virtuality of the exchanged photon, Q^2. At high Q^2 (highly virtual photons), similar transitions should become effective also for light vector mesons. This is indeed supported by first results from HERA [15].

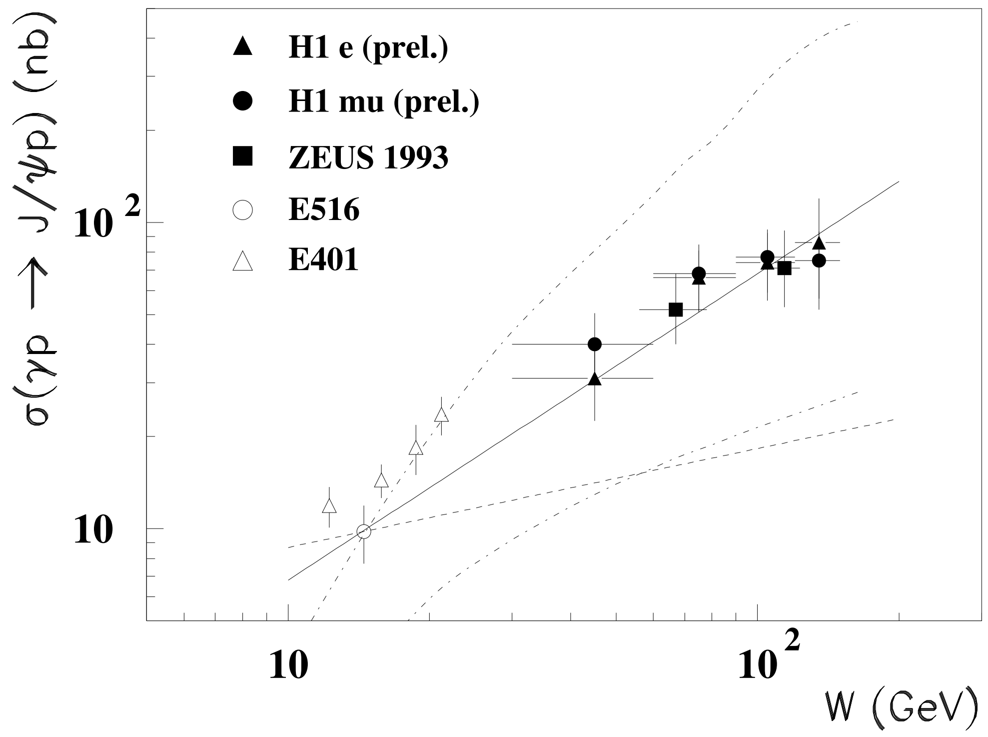

Figure 3: Photoproduction cross section for elastic J/ψ production as a function of $W_{\gamma p}$. The squares (circles and triangles) represent results of the ZEUS (H1) analyses and the other symbols earlier measurements by fixed-target experiments. The dashed (solid) line shows $\sigma_{\gamma p} \sim W_{\gamma p}^{4\varepsilon}$ with $\varepsilon = 0.08$ ($\varepsilon = 0.25$). Both curves are normalized to the E516 data point. The band spanned by the dashed-dotted lines indicates the prediction of a perturbative QCD model, using the upper and lower limits of the gluon momentum density as extracted in LO by the ZEUS experiment.

4 Inelastic photoproduction of J/ψ mesons

Candidate events for inelastic J/ψ photoproduction are reconstructed from two identified leptons and selected by a cut in z,

$0.45 < z < 0.90$	H1 (muon analysis)
$0.40 < z < 0.90$	ZEUS (electron analysis)
$0.20 < z < 0.90$	ZEUS (muon analysis)

The lower cut on z reduces the contribution from photon proton scattering processes where the hadronic component of the photon interacts with the proton (resolved processes) and a large fraction of other background processes. The upper cut in z largely excludes the contribution from elastic and diffractive photon proton scattering. It also ensures that the measurement is performed in a kinematical region where NLO calculations are reliable [4]. The J/ψ signal found by the H1 analysis is shown for example in fig. 2b. The background is mainly due to muons from semileptonic decays of hadrons and misidentified pions. For comparison with NLO calculations, the measurement is extrapolated to $z = 0$. The extrapolation amounts to about 10%.

The photoproduction cross section is shown in fig. 4 as a function of $W_{\gamma p}$ and compared to NLO calculation [4] for two different parametrizations of the parton densities in the proton and for different values of the charm quark mass and the strong coupling constant, which are the main sources of theoretical uncertainty. The measured cross section is almost a factor 2 larger than the highest predictions. The difference in the normalization is smallest if $\alpha_s \approx 0.3$ (a rather large value) and $m_c \approx 1.4\,\mathrm{GeV}$ (a comparatively low value). The $W_{\gamma p}$ dependence is best described if a gluon density distribution function is used which has a strong increase towards

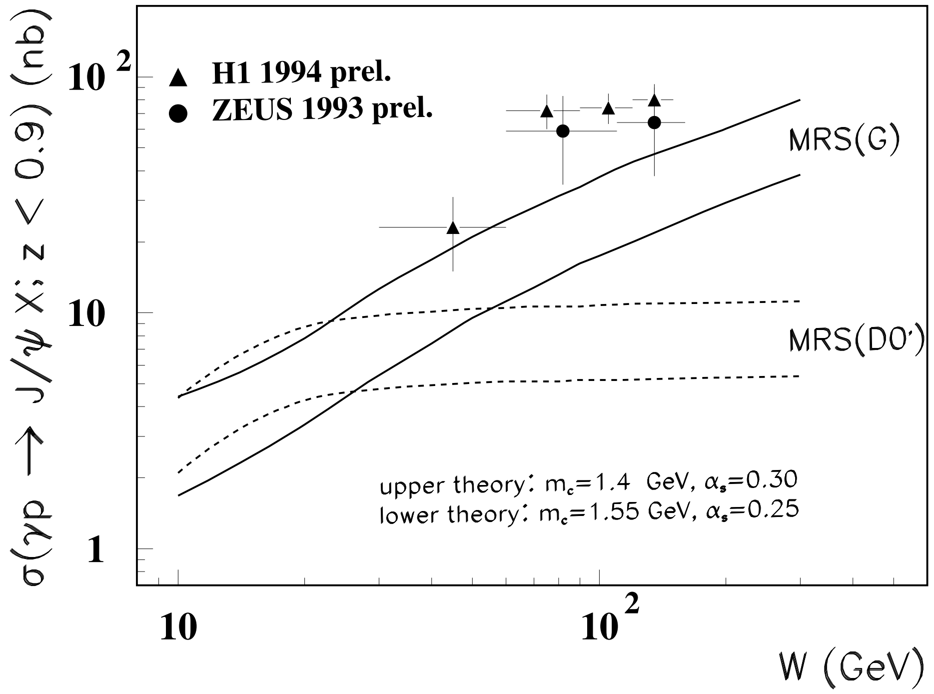

Figure 4: Photoproduction cross section for inelastic J/ψ production as a function of $W_{\gamma p}$. The theoretical curves are NLO calculations for different proton parton density parametrizations. The upper and lower curves indicate the uncertainty due to variations of the mass of the charm quark and the value of the strong coupling constant.

low x, such as MRS G [16]. The difference in absolute magnitude of the cross sections is under investigation, theoretically and experimentally. The sensitivity to the parton density functions will improve with larger statistics.

5 Conclusions

At HERA, elastic and inelastic production of J/ψ mesons are being studied and provide valuable information about the underlying production mechanisms. The elastic photoproduction cross section shows an increase with $W_{\gamma p}$ which can be parametrized by $W^{4\varepsilon}, \varepsilon \approx 0.2 \div 0.25$. A flat increase, as observed in hadroproduction ($\varepsilon = 0.08$) does not describe the HERA data. The cross section for inelastic J/ψ production is almost a factor of two larger than predicted in the colour singlet model, including relativistic and NLO corrections. The measured $W_{\gamma p}$ dependence can be used to constrain the gluon distribution function in the proton. The data favour a gluon density which is increasing towards low x. This is in agreement with other measurements at HERA, e.g. scaling violations of the proton structure function at low x [17].

In the near future, HERA experiments will provide a first direct measurement of the gluon density distribution in the proton from heavy flavours, a better understanding of the underlying production mechamisms of (light and heavy) vector meson production, and cross section measurements of higher mass particles ($\psi\prime, \Upsilon$). The interesting transition region between the soft pomeron and perturbative QCD processes, now accessible with vector meson production, will be explored in detail.

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References

[1] H. Jung, G.A. Schuler, and J. Terron, Int.Journ.Mod.Phys. A32 (1992) 7955
G.A. Schuler and J. Terron, DESY 92-017 (1992)

[2] E.L. Berger and D. Jones, Phys.Rev. D23 (1981) 1521

[3] H. Jung, D. Krücker, C. Greub, and D. Wyler, Z.Phys. C60 (1993) 721

[4] M. Kraemer, J. Zunft, J. Steegborn, and P.M. Zerwas, Phys.Lett. B348 (1995) 657

[5] J.J. Sakurai, Phys.Rev.Lett. 22 (1969) 981

[6] M. Ryskin, Z.Phys. C57 (1993) 89

[7] M. Derrick *et al.*(ZEUS Coll.), "The ZEUS Detector", Status Report, DESY (1993)

[8] I. Abt *et al.* (H1 Coll.), "The H1 Detector at HERA," DESY 93-103 (1993)

[9] C.F. Weizsäcker, Z.Phys. 88 (1934) 612
E.J. Williams, Phys.Rev. 45 (1934) 729

[10] M. Binkley *et al.*(E401 Coll.), Phys.Rev.Lett. 48 (1982), 73
B.H. Denby *et al.*(E516 Coll.), Phys.Rev.Lett. 52 (1984), 795

[11] M. Derrick *et al.*(ZEUS Coll.), Phys.Lett. B350 (1995) 120

[12] A. Donnachie and P.V. Landshoff, Nucl.Phys. B244 (1984), 322; Nucl.Phys. B311 (1989) 509; Phys.Lett. B348 (1995) 213

[13] A. Donnachie and P.V. Landshoff, Phys.Lett. B296 (1992), 227

[14] M. Derrick *et al.*(ZEUS Coll.), Phys.Lett. B342 (1995) 417

[15] M. Derrick *et al.*(ZEUS Coll.), DESY 95-133 (1995)
I. Kenyon, Proc. VIth Blois Workshop on Elastic and Diffractive Scattering, to be published

[16] A.D. Martin, R.G. Roberts, and W.J. Stirling, RAL-94-055 (1994)

[17] I. Abt *et al.*(H1 Coll.), Phys.Lett. B321 (1994) 161
M. Derrick *et al.*(ZEUS Coll.), Phys.Lett. B345 (1995) 576
S. Aid *et al.*(H1 Coll.), DESY 95-081 (1995), DESY 95-086 (1995)