Inelastic charmonium production at HERA

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New results with increased statistics are presented for the production of J/ψ in the photoproduction limit $Q^2 \to 0$. Electroproduction has been analysed for $2 \lesssim Q^2 \lesssim 80\,\mathrm{GeV}^2$ in a completely inclusive way and with an inelastic selection aimed at retaining possible colour octet contributions. Calculations based on the colour singlet model in NLO are compared to the photoproduction data and good agreement is found. Results from calculations within the NRQCD approach including colour octet contributions are confronted with the data in both Q^2 regimes. A Monte Carlo model based on soft colour interactions is furthermore compared to the inclusive cross sections.

1. INTRODUCTION

Due to increased statistics available from the year 1997 new data on charmonium (J/ψ, ψ') and Υ production have been presented by H1 and ZEUS. Here we will concentrate on "inelastic" J/ψ production as opposed to the diffractive processes [1] which dominate the cross section at low Q^2. HERA was operating with positrons (27.5 GeV) and protons (820 GeV) yielding a center of mass energy of 300 GeV. Standard variables for lepton proton scattering will be used: Q^2, the negative four momentum squared of the exchanged photon, W, the center of mass energy of proton and exchanged photon, and $z = \frac{E_\psi}{E_\gamma}$ the energy of the J/ψ relative to that of the exchanged photon in the proton rest frame.

$$z = \frac{P_\psi \cdot P}{P \cdot q} \approx \frac{E_\psi}{E_\gamma} \qquad (1)$$

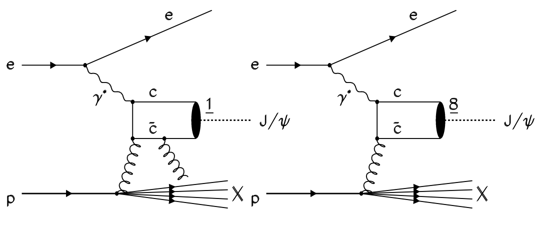

Figure 1. J/ψ production via photon gluon fusion in the colour singlet model(left) and in the colour octet (right) model.

2. THEORY AND MODELS

Inelastic J/ψ production at HERA proceeds via exchange of almost real ($Q^2 \sim 0$) or virtual photons ($Q^2 > 2$ GeV^2) and is dominated by photon gluon fusion. At low z values resolved processes may become important at $Q^2 \sim 0$ while at high z diffractive processes are large. In the fixed target regime data for inelastic J/ψ production were well described by the colour singlet model (CSM) and this is still found to be true at HERA.

As is well known the CSM fails to describe charmonium production in $p\bar{p}$ collisions at high p_T [7]. Colour octet contributions have been proposed for an adequate description. The NRQCD factorisation approach (NRQCD = Non Relativistic QCD) [8] describes any process $A + B \to J/\psi + X$ as a sum over colour singlet and colour octet contributions.

Whereas the transformation of a colour singlet $c\overline{c}$ pair which is in a $^3S_1$ state[1] into a J/ψ can be related to the measured semileptonic decay width, the transition of a colour octet state to

[1]Spectroscopic notation is used, $^{2S+1}L_J$

a J/ψ meson is non–perturbative. Long distance matrix elements describing these transitions are at present not calculable and are introduced as parameters in the theoretical calculations. The predictions for the cross section at HERA use the long range transition matrix elements extracted from the $p\overline{p}$ data.

The Monte Carlo model of soft colour interactions (SCI) [15] is an alternative approach, which has been quite successful in describing production of "onia" in $p\overline{p}$ collisions. In this model coloured $c\bar{c}$ pairs are produced in a hard process including parton showers to simulate higher orders. Then additional colour interactions at a scale below the pQCD cut–off are proposed which alter the colour configuration of the final state and may lead to production of colour singlet states. At HERA these soft colour interactions follow production of a $c\overline{c}$ state via photon gluon fusion. They are proposed to describe diffractive as well as inelastic production of J/ψ mesons. The SCI model gives an absolute prediction for the cross section. This model is implemented, for ep collisions, in the Monte Carlo generator AROMA [16].

3. RESULTS ON PHOTOPRODUCTION

The ZEUS collaboration has updated their photoproduction data [2] using essentially the same analysis procedure as previously [5]. The data cover a range of $40 \leq W \leq 180$ GeV. The inelastic selection requires – in addition to the decay leptons of the J/ψ– an energy deposition in the "forward" region of the detector, i.e. the direction of flight of the proton. A cut $0.4 < z < 0.9$ is introduced and a small correction applied against diffractive J/ψ production with proton dissociation.

The $\gamma\, p$ cross section derived from the new data as function of W is shown in fig. 2. The data agree well with the next to leading order pQCD calculation in the colour singlet model [9]. In fig. 3 the z distribution is shown along with previous results from H1. Also here the data are well described by the mentioned NLO prediction derived within the CSM.

Originally the z distribution was thought to distinguish clearly between colour octet and

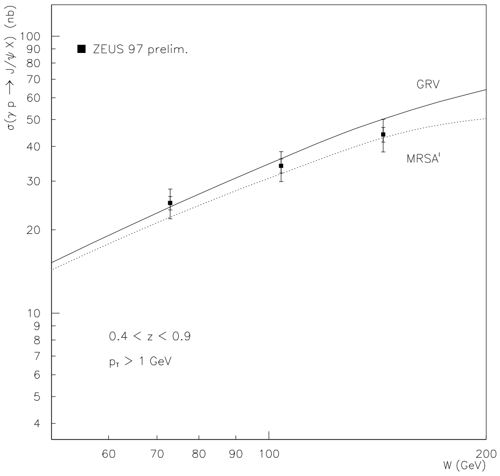

Figure 2. Inelastic J/ψ photoproduction (data from [2]): cross section as function of the photon proton center of mass energy W for $0.4 < z < 0.9$ and $p_T > 1\,$GeV. The lines correspond to the NLO predictions from [9] with GRV or MRSA' parton density functions ($m_c = 1.4$ GeV and $\Lambda_{QCD} = 300$ MeV).

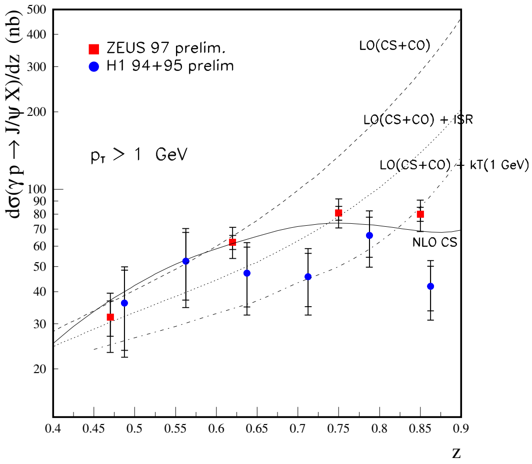

Figure 3. $d\sigma/dz$ for $50 < W < 180\,$GeV and $p_T > 1\,$GeV. The NLO computation is shown as a dashed line. The dotted and dash-dotted lines are given by the sum of the colour singlet and the colour octet leading order calculations performed in [11] and in [12] (see text).

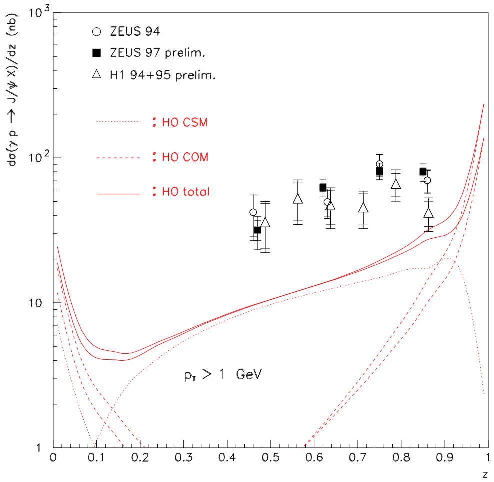

Figure 4. Inelastic J/ψ photoproduction: $d\sigma/dz$ Data from [2,4,5]. The theoretical curves are from [13](see text).

colour singlet mmechanisms. In fig. 3 in addition to the NLO CSM curve calculations using the NRQCD/factorisation approach [10–12] are shown. These are in leading order (LO). The upper (dashed) curve was calculated using the transition matrix elements extracted originally from $p\overline{p}$ data in LO and shows a strong rise towards high z values which overshoots the data. Subsequently it was realised that higher order effects (gluon radiation and/or effects of finite k_T) may have a large effect on the values of the long distance matrix elements. Estimating these resulted in a reduction of the size of the long distance matrix elements relevant for HERA. The two lower curves in fig. 3 were derived using these lower *approximate* matrix elements as explained in refs. [10–12]. The predicted rise is decreased and the curves come closer to the data. In fig. 4 the data shown in fig. 3 and previous data from the ZEUS collaboration are shown. A prediction [13] covering the full z-range including the region of "resolved photon" contributions is given for comparison. Along with CSM curves predictions using decreased long distance matrix elements extracted from the $p\overline{p}$ data estimating effects of higher orders are shown. The predictions for HERA are in leading order and are found to lie below the data by approximately a factor 3.

4. INCLUSIVE AND INELASTIC ELECTROPRODUCTION OF J/ψ

H1 has for the first time determined differential cross sections for inclusive and inelastic J/ψ production at $Q^2 > 2$ GeV^2 [6], covering a range $40 \leq W \leq 180$ GeV. For the inclusive differential cross sections a cut $z > 0.2$ or 0.5 is applied for the J/ψ decay into muons and electrons, respectively. Acceptances and efficiencies are corrected using a Monte Carlo simulation containing diffractive and inelastic contributions.

The results for the inclusive selection are shown in fig. 5 in the form of differential cross sections $d\sigma/dQ^2$, $d\sigma/dp_{t,\psi}^2$, $d\sigma/dz$ and $d\sigma/dy^*$, where y^* denotes the rapidity of the J/ψ in the photon proton center of mass system. The model of soft colour interactions is compared to the data. The shapes of most differential distributions are rather well described while the absolute height of the model is below the data. An exception is the z distribution which shows large discrepancies in particular at high z values. This may partially explain the discrepancies in absolute normalisation observed in the other distributions. The difference between SCI model and data at low z values is believed to be due to missing "hard" contributions, i.e. emission of hard gluons.

The inelastic selection is performed by determining differential cross sections for a high mass M_X of the hadronic system X produced together with the J/ψ(see diagrams in fig. 1). This is achieved indirectly by demanding a large energy deposition in the forward region of the detector, $E_{fwd} > 5$ GeV and correcting the data for $M_X > 10$ GeV using Monte Carlo simulations. The effect of this procedure is best seen in the z and y^* distributions shown in fig. 6. The cut on M_X has a large effect at high z where the diffractive contributions are expected. The rapidity of the J/ψ in the photon proton center of mass system is affected at values above $y^* > 2.5$. Note that large values of y^* correspond to the direction of the exchanged photon.

In fig. 7 the resulting cross sections for $M_X > 10$ GeV are shown together with the predictions in the framework of NRQCD. The data are seen to be far above the CS contributions, which are shown separately. On the other hand taking into account colour octet contributions the predictions are above the data. The shape of the latter leaves, however, much room for improvement, in particular in the rapidity y^* in the $\gamma^* p$ center of mass system. Note that the NRQCD calculations are performed at the parton level, no smearing due

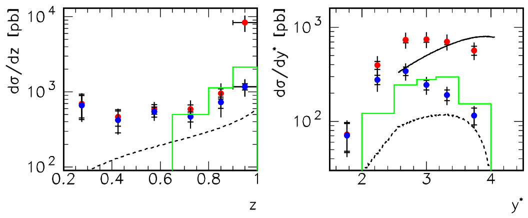

Figure 6. Differential cross sections for the inclusive (open points) and inelastic ($M_X > 10$ GeV, black points) $ep \to e\ J/\psi\ X$ process. $d\sigma/dz$ and $d\sigma/dy^*$ are shown. The curves give the NRQCD predictions as in fig. 7 while the histogram is calculated using the SCI model as in fig. 5.

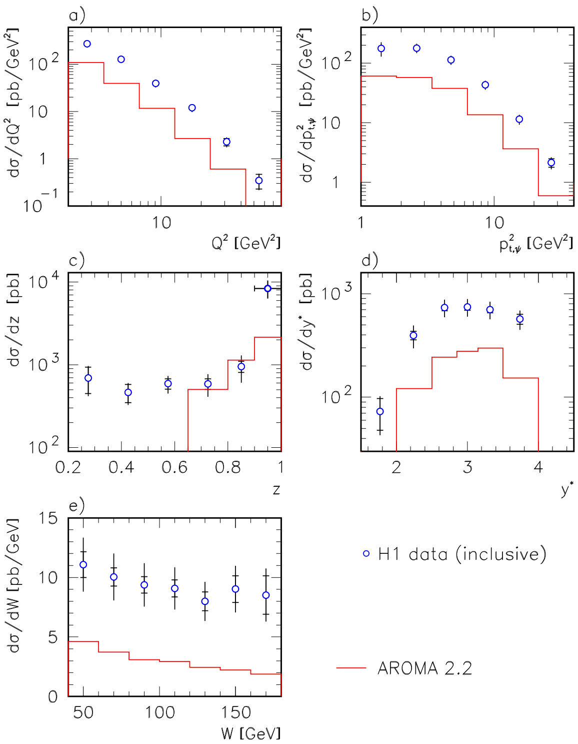

Figure 5. Differential cross sections for inclusive (open dots) J/ψ production as a function of Q^2, $p_{t,\psi}^2$, z, y^* and W. The inner error bars give the statistical error, the outer errors are the statistical and systematical uncertainties added in quadrature. A prediction by AROMA2.2 with soft colour interactions SCI (dotted histogram) is also shown.

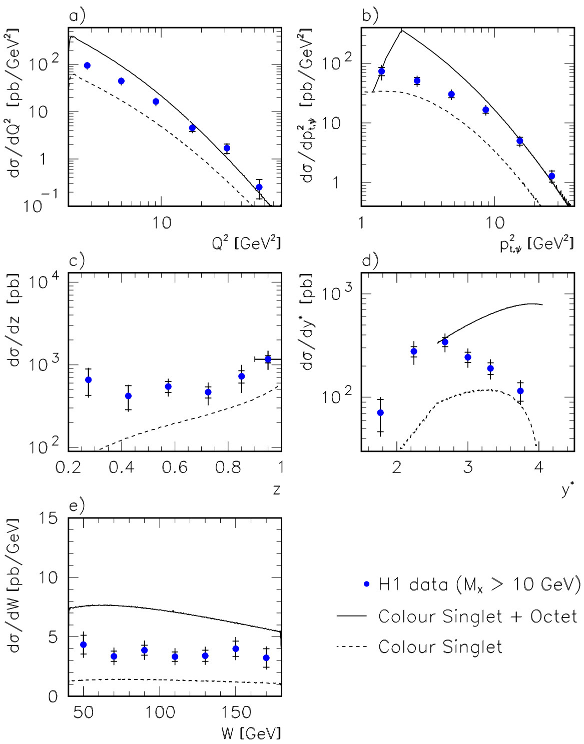

Figure 7. Differential cross sections for inelastic (full dots) J/ψ production as a function of Q^2, $p_{t,\psi}^2$, z, y^* and W. The curves show the NRQCD predictions, the colour singlet contribution (dashed line) and the sum of colour singlet and colour octet contributions (full line).

to the transition into J/ψ is taken into account.

4.1. Decay angular distribution

The measurement of the polarisation of the J/ψ meson is interesting and may distinguish different production mechanisms. The decay angular distribution in the helicity frame is shown in figure 8. It is predicted to be of the form:

$$\frac{d\sigma}{d\cos\theta^*} \sim 1 + \alpha\cos^2\theta^* \ .$$

For the colour singlet model $\alpha \approx 0.5$ is expected, for the colour octet model $|\alpha| \lesssim 0.5$, negative, zero or positive depending on which $c\bar{c}$ configuration dominates in the production. The measured values are $\alpha = 0.54^{+0.29}_{-0.26}$ for the inclusive selection and $\alpha = 0.77^{+0.44}_{-0.38}$ in the inelastic case, both compatible with the colour singlet prediction.

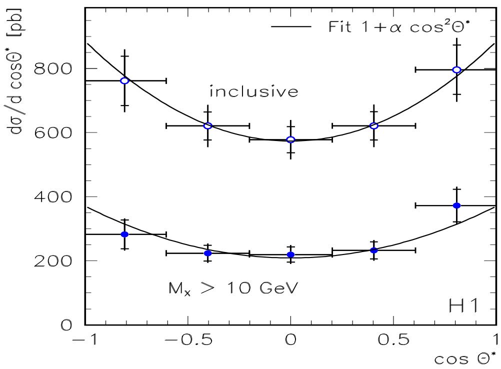

Figure 8. Angular distributions for the inclusive and inelastic selections at $Q^2 > 2$ GeV^2.

4.2. Comparison to photoproduction

For the comparison with photoproduction data the total $\gamma^* p$ cross section at $Q^2 > 2$ GeV^2 as function of W is calculated for the inclusive case and for an inelastic selection with $z < 0.9$, the same cut as applied in photoproduction. The results are shown in figure 9 together with HERA results for $Q^2 \approx 0\,\mathrm{GeV}^2$ [3,5]. The W dependence of the cross sections is very similar for photoproduction and leptoproduction. It can be parametrised by a power law W^δ with $\delta = 0.95 \pm 0.11, \delta = 0.89 \pm 0.20$ and $\delta = 0.91 \pm 0.26$ for the inclusive and inelastic leptoproduction and for inelastic photoproduction, respectively.

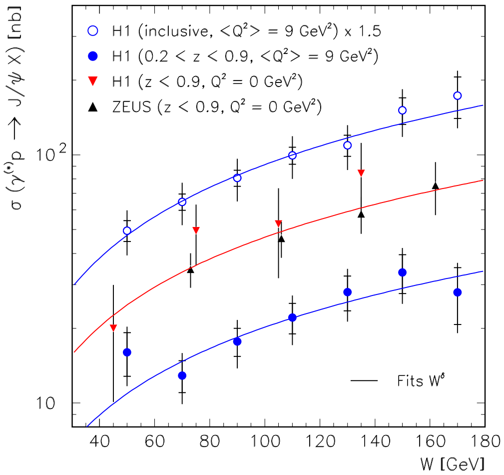

Figure 9. Total cross section for $\gamma^{(*)}p \to J/\psi X$ Data for photoproduction ($Q^2 \sim 0$ [2,5,3]) are shown. For $Q^2 > 2$ GeV^2[6] the inclusive (scaled by a factor 1.5) and inelastic cross sections are shown. A cut $z < 0.9$ is common to all data while the treatment of the low z end differs slightly.

5. SUMMARY

Inelastic J/ψ production is studied in photoproduction and at $Q^2 > 2$ GeV^2. The photoproduction data are found to be well described by the colour singlet model alone in next to leading order. Theoretical deviations due to colour octet contributions are still under debate and do not seem to play a major role in the measurements. At $Q^2 > 2$ GeV^2 inclusive differential cross sections have been extracted. The model of soft colour interactions gives a rather good description of their shapes while the absolute height is below the data. Inelastic cross sections have been extracted avoiding a cut on z in order to retain possible colour octet contributions. LO colour singlet and colour octet predictions (at parton level) were compared to the data. Neither shape nor magnitude of the measurements is adequately described and calls for adjustments of parameters and probably also for inclusion of higher order effects.

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