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Inelastic J/ψ production at HERA

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Inelastic J/ψ photoproduction is an interesting area where one can test QCD predictions. This article reviews the recent experimental results obtained by the ZEUS and H1 Collaborations. Single differential and double differential cross sections have been measured by the H1 Collaboration using an integrated luminosity of 166 pb^{-1}, taken in the years 2006-2007. The J/ψ decay angular distributions have been measured in inelastic photoproduction by the ZEUS Collaboration, with an integrated luminosity of 468 pb^{-1}. These results have an increased precision compared to previous analyses. The measurements are compared to various theoretical predictions at leading and next-to-leading order in QCD.

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1. Introduction

The production of heavy quarkonia in high energy *ep* collisions provides an ideal and to some extent unique laboratory where our understanding of nonperturbative QCD and its interplay with perturbative QCD may be tested in a controlled framework. In the following, firstly we give a brief summary of the theory, then in section 3 we show the differential cross sections measurements made by the H1 Collaboration and in section 4 the measurements of the J/ψ polarization (helicity) made by the ZEUS Collaboration. Both measurements were done in the photoprodutcion regime [1]. The results are compared with theoretical predictions at leading and next-to-leading order in QCD. Finally we give conclusions in section 5.

2. Theory

In *ep* collisions charmonium can be produced inelastically both through direct photon and resolved photon processes[2]. In direct photon processes, the photon couples directly to a parton in the proton, whereas in resolved photon processes, the photon acts as a source of partons, one of which participates in the hard interaction. The charmonium state can emerge from the hard interaction either immediately with the right values of spin, angular momentum and colour, **colour singlet (CS) model**, or in a coloured $c\bar{c}$ state, **colour octet (CO) model**, which is followed by a long-distance transition to charmonium and light hadrons. This transition is parameterised through process-independent matrix elements, whose values are extracted from experimental data. The theory, incorporating in a coherent manner CS and CO terms, is called Non-Relativistic QCD (NRQCD). Despite these developments the range of applicability of these approaches to the practical case of charmonium is still subject of debate, as is the quantitative verification of factorisation between hard cross sections and matrix elements. Apart from the previous models, there is also the k_T-factorisation method which, starting from the CS model, uses k_T factorisation in an attempt to take into account initial-state radiation through parton distributions that depend on the parton's transverse momentum k_T, as well as on the parton's longitudinal momentum fraction x. The k_T-dependent parton distributions are not very well known phenomenologically, and there are possibly unresolved theoretical issues, such as the universality of the k_T-dependent parton distributions. In this situation cross checks between various processes and predictions of different observables (for example quarkonium polarisation and differential cross sections) are crucial in order to assess the importance of different quarkonium production mechanisms, as well as the limitation of a particular theoretical approach. We have also to remember that next-to-leading order (NLO) calculations exist only in the photoproduction regime, restricted to the CS model. Within NRQCD and k_T frameworks the calculations are limited to leading order (LO) both in photoproduction and electroproduction regimes.

3. Differential cross sections measurements

The new data from the H1 Collaboration [2] correspond to an integrated luminosity of 166

[1]When the virtuality of the exchanged photon (Q^2) is almost zero, one speaks of photoproduction regime, when the virtuality is greater than 1 GeV^2 we are in the electroproduction regime.

[2]An exhaustive review of the quarkonia production can be found in [1].

pb^{-1} taken during the years 2006-2007. The J/ψ mesons were identified through their decay into muon pairs. Additional tracks were required in order to suppress events from J/ψ and $\psi(2S)$ diffractively produced, and select true inelastic events. In each event the absence of the scattered electron was required in order to select photoproduction. The phase space region [3] was defined as: $p_T > 1$ GeV, $60 < W < 240$ GeV, $0.3 < z < 0.9$. In Fig. 1 (a) and (b) the inelastic J/ψ photoproduction differential cross sections as function of p_T^2 and z are shown, respectively. The circles correspond to these new H1 measurements, while the stars correspond to a previous publication [3], good agreement is seen between these two independent data samples. Between the various theoretical curves plotted, two are in good agreement with the data for both cross sections: a NLO calculation performed in the CS model [4] and the CASCADE [4] Monte Carlo [5]. We have to observe that this NLO calculation used rather extreme values for the renormalization scale [5], they have the effect of artificially increasing the normalization. A recent NLO calculation [8] using $\mu_R = \mu_F = 4m_c$ (with $m_c = 1.5$ GeV) gives predictions much lower than the data.

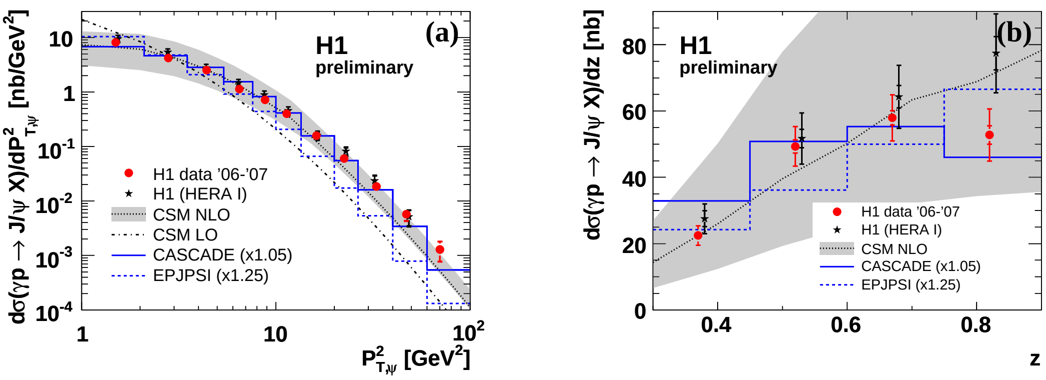

Figure 1: Inelastic J/ψ differential cross sections as function of p_T^2 (a) and z (b). The inner (outer) error bars correspond to the statistical (total) uncertainty. The theoretical curves are described in the text.

In Fig. 2 (a) the differential cross section as function of p_T^2 in bins of z and in Fig. 2 (b) the differential cross section as function of z in bins of p_T are shown. The CASCADE Monte Carlo gives an overall good description for both cross sections.

4. Polarization measurements

The decay angular distributions of the J/ψ provide another observable (different from the differential cross sections) that can clarify the underlying production mechanism (CS vs. CO but also collinear vs. k_T factorisation). The helicity analysis made by the ZEUS Collaboration [6] used an integrated luminosity of 468 pb^{-1} selecting the J/ψ's through their decay into muon pairs. It was performed in the so called "target frame" in which the quantization axis is taken to be the

[3] p_T is the transverse momentum of the J/ψ in the laboratory frame, W is the photon-proton centre of mass energy, the inelasticity variable z is equal to the fraction of the energy of the incoming photon taken by the outgoing J/ψ in the proton rest frame.

[4] CASCADE Monte Carlo is based on LO CS model, k_T factorization and CCFM evolution equations.

[5] $\mu_R = \mu_F = \max[\sqrt{2}m_c, \frac{1}{2}\sqrt{m_c^2 + p_T^2}\,]$ with $1.3 \le m_c \le 1.5$ GeV.

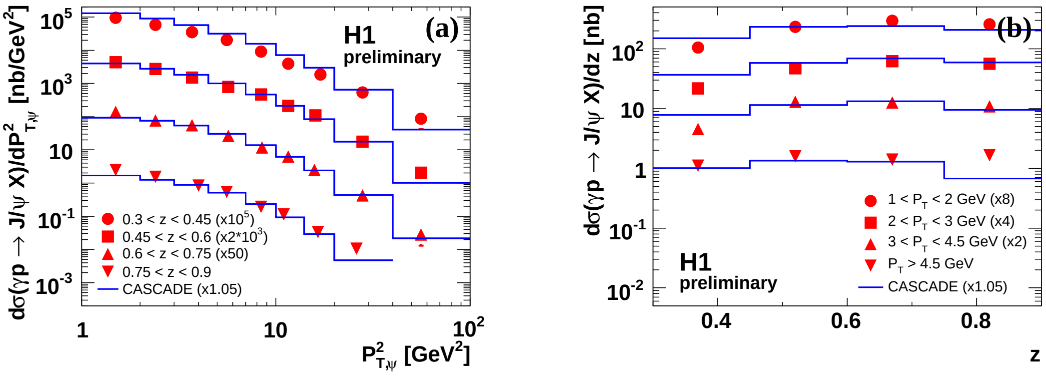

Figure 2: Inelastic J/ψ differential cross sections as function of p_T^2 in bin of z (a) and as function of z in bins of p_T (b). The inner (outer) error bars correspond to the statistical (total) uncertainty. The theoretical curves are described in the text.

opposite of the incoming proton direction in the J/ψ rest frame. The differential cross sections in θ and ϕ can be parametrized as:

$$\frac{d\sigma}{d\theta} \propto 1 + \lambda \cos^2\theta, \qquad \frac{d\sigma}{d\phi} \propto 1 + \frac{\lambda}{3} + \frac{\nu}{3}\cos 2\phi,$$

where λ and ν, the polar and azimuthal angular parameters, are functions of p_T and z. In Fig. 3 (a), the ZEUS data are shown for λ vs. p_T in the phase space region $0.4 < z < 1$ and $50 < W < 180$ GeV. The values $\lambda = -1$ and $\lambda = +1$ correspond to fully longitudinal and transverse polarization, respectively. The data are consistent with being flat with increasing p_T. In Fig. 3 (b) the ZEUS data are shown for ν vs. z in the phase space region $p_T > 1$ GeV and $50 < W < 180$ GeV. The data are flat for medium z while seem to increase at low and high z. The data are compared with various theoretical calculations: LO CS [7], LO CS + CO [7], NLO CS [8] and LO k_T [9]. None of the predictions are able to describe all aspects of the data. The NLO CS calculation for $p_T > 1$ GeV suffers from large scale uncertainties [10], in order to avoid this problem, measurements and calculations were repeated increasing the p_T cut to 2 GeV and 3 GeV. In Fig. 3 (c) and (d) the λ and ν parameters, respectively, are shown as function of z for $p_T > 3$ GeV. The NLO CS calculation has now smaller uncertainties, but agrees with the data only for the ν parameter.

5. Conclusions

The H1 Collaboration has measured single and double differential cross sections for the inelastic J/ψ photoproduction using an integrated luminosity of 166 pb^{-1}. The results are in good agreement with CS NLO calculations and with k_T factorisation model as implemented in CASCADE. However, no strong conclusions about the presence of the CO terms can be derived due to the large systematic uncertainties present in the NLO calculations. The J/ψ helicity distributions in the inelastic photoproduction regime have been measured by the ZEUS collaboration using a luminosity of 468 pb^{-1}. The results are compared to LO QCD predictions both in the CS, CS+CO and k_T factorisation frameworks and also with NLO CS calculations. None of the present predictions can describe all aspects of the data.

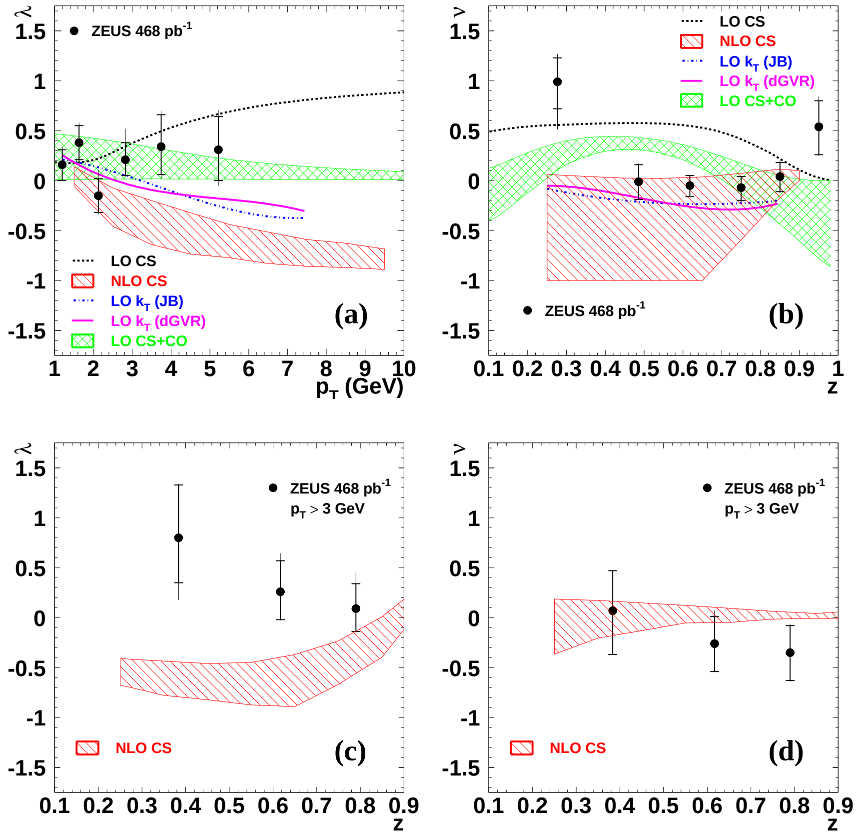

Figure 3: Distribution of the helicity parameter λ as a function of p_T, (a), and of ν as a function of z, (b). In (c) and (d) the helicity parameters λ and ν are shown as function of z, respectively, for $p_T > 3$ GeV. The inner (outer) error bars correspond to the statistical (total) uncertainty. The theoretical curves are described in the text.

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