Inelastic photo- and electroproduction of charmonium

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Abstract

Measurements of inelastic production of charmonium with the ZEUS detector at HERA are presented. J/ψ and ψ' mesons have been identified using the decay channel $\psi \to \mu^+\mu^-$. The data, corresponding to an integrated luminosity of $38\,\mathrm{pb}^{-1}$ in photoproduction and $73.3\,\mathrm{pb}^{-1}$ in electroproduction, are confronted to theoretical predictions.

1 Introduction

Inelastic production of charmonium involves two stages: the creation of a heavy quark pair at short distances and the subsequent formation of the ψ bound state which occurs at long-distance scales. In the inelastic process $e\,p \to e\,\psi\,X$, the $c\bar{c}$ pair production is dominated by photon-gluon fusion, $\gamma^* g \to c\bar{c}$, and can be calculated in perturbation theory. The ψ bound state can be considered to be formed by a $c\bar{c}$ pair in either a colour singlet (CS) or colour octet (CO) state. In the colour singlet model (CSM) only CS contribution is assumed. In the framework of non-relativistic QCD (NRQCD) both CS and CO contributions exist and the latter contribution is parametrised using a set of long distance matrix elements tuned to describe hadroproduction data.

In the semi-hard or k_T-factorisation approach, based on non-collinear parton dynamics governed by the BFKL evolution equations, effects of non-zero initial gluon virtuality (transverse momentum) are taken into account.

The inelasticity, z, which is the fraction of the virtual photon energy transferred to the ψ in the proton rest frame, is sensitive to the various production mechanisms. CS processes are expected to contribute to the region of medium z values, whereas CO (and diffractive) processes populate the high-z region. Resolved-photon processes, in which the photon acts as a source of incoming partons, populate low values of z.

2 Charmonium photoproduction

In photoproduction, charmonium production was measured by ZEUS [1] in the kinematic range $50 < W < 180\,\mathrm{GeV}$, where W is the photon-proton centre-of-mass energy, and $0.2 < z < 0.9$.

The ψ' to J/ψ cross-section ratio was also measured and used to estimate the fraction of J/ψ mesons coming from ψ' cascade decays. This value is about 15%, consistent with expectations. Hence all presented theoretical predictions of the J/ψ differential cross sections were scaled by 1.15.

In Fig. 1(a), comparison of the data with the CSM calculation [2] in LO and NLO (available only for the direct photon process) is shown. The p_T^2 spectrum in LO (KZSZ(LO, CS)) is considerably softer than one observed in the data. The NLO calculation (KZSZ(NLO, CS)) describes well both the shape and normalisation of the data, although theoretical uncertainties are large.

The NLO calculation also describes well the inelasticty distribution shown in Fig. 1(b). Kinematic limitations important at phase space boundaries (high z values) were considered [3] in the framework of NRQCD (BSW(LO, CS)

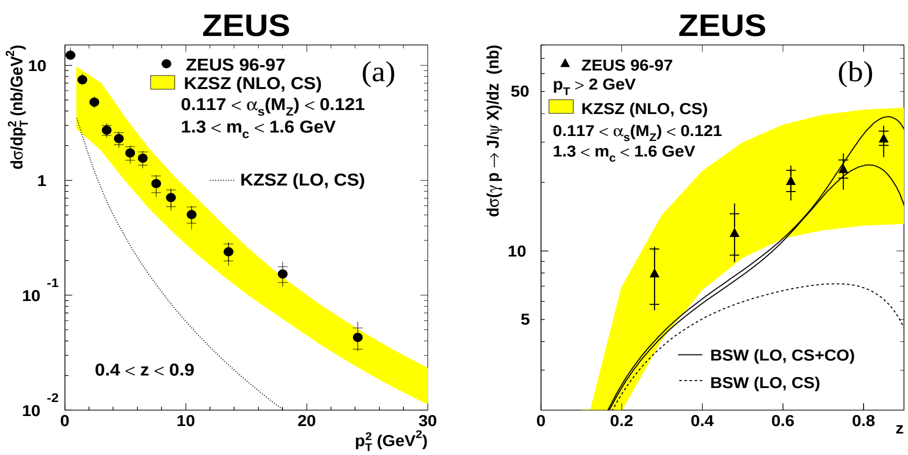

Figure 1: Photoproduction of J/ψ mesons. Differential cross sections as a function of (a) transverse momentum squared and (b) inelasticity. The data are compared to an NLO CSM calculation (shaded band), where the spread is due to uncertainties on m_c and Λ_{QCD}, (a) LO CSM calculation (dotted line) and (b) LO NRQCD calculation with soft gluon emission resummation, including CS terms (dashed line) and sum of CS and CO terms (solid lines), where the spread is due to the uncertainty on the shape-function parameter.

and BSW(LO, CS + CO)) and a resummation procedure was introduced. The resummation leads to a good agreement of the sum of CS and CO contributions with the data at high z. At lower z values the discrepancy is likely to be due to resolved contributions, which were not taken into account in the calculation. The CS contribution alone is below the data.

3 Electroproduction of J/ψ

The measurement of inelastic electroproduction of J/ψ was performed in the kinematic range $2 < Q^2 < 80\,\mathrm{GeV}^2$, $50 < W < 250\,\mathrm{GeV}$, $0.2 < z < 0.9$ and $-1.6 < Y_{\mathrm{lab}} < 1.3$, where Y_{lab} is the rapidity of J/ψ in the laboratory frame. In Fig. 2, the data are compared to predictions in the framework of NRQCD [4] and in the CSM with k_T-factorisation [5].

The CS contributions (KZ(CS)) and the sum of CS and CO contributions (KZ(CS + CO)) of the NRQCD predictions are shown separately. The uncertainty shown for the theoretical calculation corresponds to variations of the charm quark mass ($m_c = 1.5 \pm 0.1\,\mathrm{GeV}$) and the renormalisation and factorisation scales (from $1/2\sqrt{Q^2 + M_\psi^2}$ to $2\sqrt{Q^2 + M_\psi^2}$). The uncertainty on the long distance matrix elements and the effect of different choices of parton density functions are also taken into account. The band shows all the uncertainties added in quadrature.

In general, the CS predictions are below the data but consistent both in shape and normalisation within the uncertainties shown. However, the prediction for the differential cross section as a function of transverse momentum squared in the laboratory system (not shown) and in the photon-proton centre-of-mass system (p_T^{*2}) are too soft compared to the data. The results in the photoproduction regime, presented in the previous section, indicate that NLO corrections are needed to describe the J/ψ transverse momentum spectrum in the framework of the CSM.

Inclusion of CO contributions leads to an excess of the NRQCD predictions over the data, especially at high z. At high values of p_T and p_T^* agreement with the data is reasonable, however at low values of transverse momenta the predictions overshoot the data.

For the prediction within the k_T-factorisation approach (LZ(kt, CS)) only one source of uncertainty was considered, namely a variation of the pomeron intercept Δ which controls the normalisation of the unintegrated gluon density used in the calculation in the form suggested by Blümlein [6]. Central values were calculated with $\Delta = 0.35$ and the uncertainty corresponds to the variation of Δ between 0.20 and 0.53. The charm quark mass used is $m_c = 1.55\,\mathrm{GeV}$. The renormalisation and factorisation scales were set to the absolute value of the

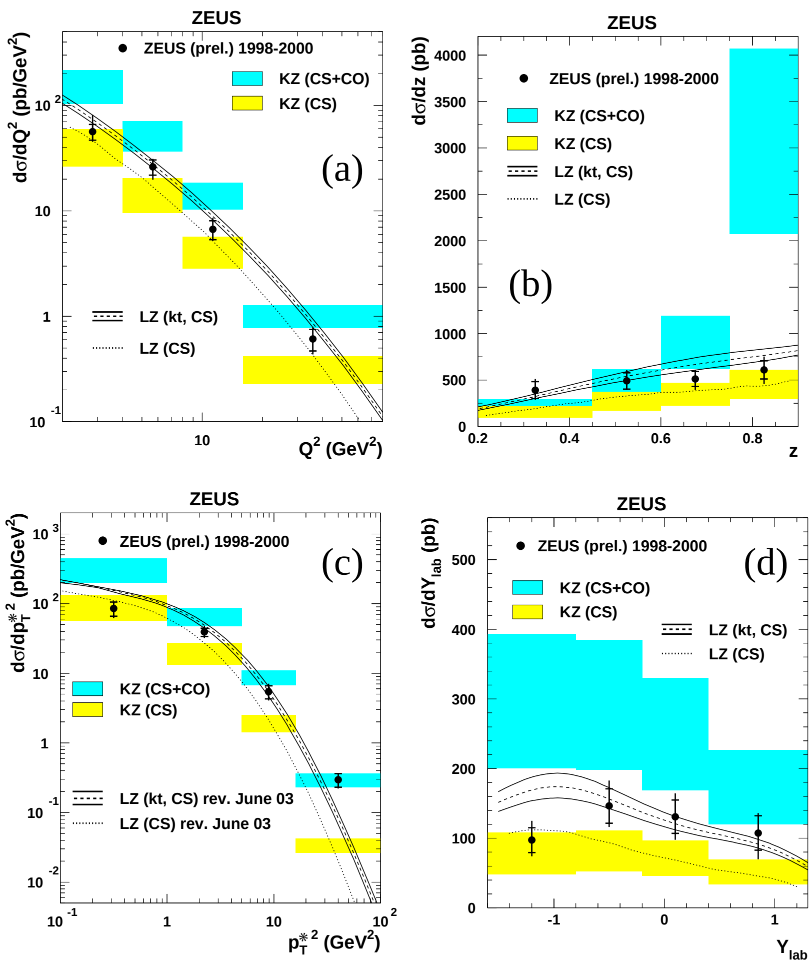

Figure 2: Electroproduction of J/ψ mesons. Differential cross sections as a function of (a) virtuality of the exchanged photon, (b) inelasticity, (c) transverse momentum squared in the photon-proton centre-of-mass system and (d) rapidity in the laboratory system. The data are compared to LO NRQCD predictions [4] (the upper band is the sum CS + CO and the lower band is CS only) and calculations in the k_T-factorisation approach within the CSM [5] (solid lines delimit the uncertainty, dashed line shows the central value). The CSM prediction in the framework of collinear factorisation [5] is also shown (dotted line).

initial gluon transverse momentum. A calculation in the framework of collinear factorisation within the CSM (LZ(CS)) was also provided [5] which is generally consistent with CS contributions of the NRQCD predictions (KZ(CS)).

Calculations based on the k_T-factorisation approach give a reasonable description of the data both in normalisation and shape. However, the predicted p_T^{*2} spectrum is softer than in the data.

4 Summary

Results on inelastic charmonium production in both photo- and electroproduction have been obtained with the ZEUS detector and compared to theoretical predictions in the CSM, calculations in the framework of NRQCD and the k_T-factorisation approach.

In photoproduction, NLO corrections to the direct photon process calculated in the colour singlet model describe well the J/ψ transverse momentum distribution. Cross sections as a function of W and z are also well described. However the theoretical uncertainties are large and hence CO contributions cannot be excluded.

In electroproduction, LO CS predictions, based on collinear perturbative QCD, are below but consistent with the data within the uncertainties, except at high p_T. The LO NRQCD predictions, including both CS and CO contributions, are generally above the data, especially at large z and small p_T^* values. At high transverse momenta, agreement with the data is reasonable, but NLO corrections are needed to draw stronger conclusions. The calculation in the k_T-factorisation approach within the colour singlet model gives an overall better description of the data.

References

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