Submitted to the
International Conference on High Energy Physics
16-22 August 2004, Beijing, China

Abstract: 5-0336,11-0337 Session: QCD hard interactions and Heavy quarks

Measurment of inelastic J/ψ production in deep inelastic scattering at HERA

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Abstract

The inelastic production of charmonium in deep inelastic scattering (DIS) has been studied with the ZEUS detector at HERA using an integrated luminosity of 73.3 pb^{-1}. J/ψ mesons were identified using the decay channel $J/\psi \to \mu^+\mu^-$. The measurment was performed in the kinematic range $2 < Q^2 < 80$ GeV^2, $50 < W < 250$ GeV, $0.2 < z < 0.9$ and $-1.6 < Y_{\rm lab} < 1.3$, where Q^2 and W are standard DIS variables, z is the fraction of the photon energy carried by the J/ψ meson in the proton rest frame and $Y_{\rm lab}$ is the rapidity of J/ψ in the laboratory frame. The measured cross sections lie above the calculations using colour-singlet contributions of the non-relativistic leading-order QCD predictions. Predictions including colour-octet contributions generally lie above the data and differ in shape to the measured differential cross sections. Calculations based on the k_T-factorisation approach give a reasonable description of the data providing an overall better description of the data than the non-relativistic QCD predictions.

1 Introduction

This paper presents a measurement of inelastic J/ψ production in deep inelastic scattering (DIS) with the ZEUS detector at HERA. The reaction $e(k)\,p(P) \rightarrow e(k')\,J/\psi(p_\psi)\,X$ (where the particle 4-momenta are shown in brackets) is studied for virtuality, $Q^2 = -q^2 = -(k-k')^2$, of the exchanged photon $Q^2 > 2\,\mathrm{GeV}^2$.

Inelastic production of charmonium involves two stages: the creation of a heavy quark pair at short distances and subsequent formation of the J/ψ bound state which occurs at long-distance scales. In DIS, the $c\bar{c}$ pair production is dominated by photon-gluon fusion $\gamma^* g \rightarrow c\bar{c}$ and can be calculated in perturbation theory. There are different approaches both to parton dynamics and to the description of the $c\bar{c}$ bound state formation, which are investigated in this paper.

The J/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) [1] only CS states contribute to the charmonium production. In the framework of non-relativistic QCD (NRQCD) [2] both CS and CO contributions exist. In NRQCD, the transition of different colour and angular-momentum states of a $c\bar{c}$ pair into the J/ψ meson is parametrised using a set of long distance matrix elements (LDMEs) tuned to describe hadroproduction data.

In the semi-hard or k_T-factorisation approach [3], based on non-collinear parton dynamics governed by the BFKL [4] evolution equations, effects of non-zero initial gluon virtuality (transverse momentum) are taken into account. This leads to the resummation of the $\log(1/x)$ terms which is important in the kinematic region of asymptotically small Bjorken-x. In the k_T-factorisation approach parton cross sections are calculated as a convolution of unintegrated (transverse momentum dependent) gluon densities and off-shell matrix elements.

The CO contributions, predicted in the framework of NRQCD, were found to be essential to describe high-p_T production of charmonium in $p\bar{p}$ collisions [5]. The transverse momentum spectrum of J/ψ mesons in $\gamma\gamma$ interactions at LEP2 [6] also appears to be well reproduced by NRQCD calculations. Measurements of the J/ψ polarisation performed by the CDF collaboration [7] revealed that data do not follow the pattern predicted by NRQCD. Similar conclusions can be drawn from recent measurements by the Belle collaboration [8].

In DIS at HERA, the inelasticity, $z = (P \cdot p_\psi)/(P \cdot q)$, which is the fraction of the virtual photon energy transfered to the J/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.

Inelastic J/ψ production at HERA was studied previously both in the photoproduction regime and in DIS [9–11]. The results on the J/ψ photoproduction were found to be in agreement with both NLO CSM and LO NRQCD predictions. The measurements of J/ψ in DIS were compared to the LO CSM and NRQCD calculations; a better agreement with the NRQCD predictions was found.

The study of J/ψ production in DIS, despite restricted statistics in comparison with photoproduction, has advantages as both resolved-photon and diffractive processes are suppressed [12].

2 Data analysis

The data sample used in the analysis was collected with the ZEUS detector in the years 1998–2000 and corresponds to an integrated luminosity of $73.3 \pm 1.6\,\mathrm{pb}^{-1}$. During that period HERA collided 920 GeV protons with 27.5 GeV electrons or positrons (centre-of-mass energy $\sqrt{s} = 318\,\mathrm{GeV}$).

A detailed description of the ZEUS detector can be found elsewhere [13, 14]. The components that are most relevant for this analysis are the uranium calorimeter (CAL) [15], the central tracking detector (CTD) [16], the small angle rear tracking detector (SRTD) [17, 18], the barrel and rear muon chambers (BMUON and RMUON) [14, 19] and the luminosity monitor [20].

Events were selected online by requiring a scattered lepton in the CAL and a muon in the muon chambers. In the offline selection additional requirements were imposed in order to suppress further the photoproduction background and select inelastic events with a J/ψ candidate identified by the presence of a pair of oppositely charged muons.

The DIS selection cuts include requirements on a reliably reconstructed scattered lepton using information from both the CAL and the SRTD. The scattered electron energy had to be greater than 10 GeV. The photon virtuality Q^2 was reconstructed from the scattered lepton with the electron method [21] and was required to be $2 < Q^2 < 80\,\mathrm{GeV}^2$. The fractional energy transfer in the photon vertex $y = (P{\cdot}q)/(P{\cdot}k)$ was reconstructed with the Σ method [22]. The photon-proton centre-of-mass energy, calculated from $W^2 = ys - Q^2$, was restricted to the range $50 < W < 250\,\mathrm{GeV}$. In addition the Z coordinate of the reconstructed vertex position had to lie within 50 cm of the nominal interaction point.

The muons from the J/ψ decays were reconstructed as two oppositely charged particles in the CTD. Each track considered in the analysis was required to be fitted to the event vertex and to have the polar angle in the range $17^\circ < \theta < 163^\circ$ and transverse momentum $p_T > 100\,\mathrm{MeV}$ in order to guarantee good reconstruction quality. One of the J/ψ decay tracks had to match a segment in the muon chambers, while another one had to match a CAL cluster with an energy deposit consistent with the passage of a minimum ionising particle (m.i.p.). To ensure high muon identification efficiency and purity the muon track was required to have $p_T > 1.4\,\mathrm{GeV}$ ($p > 1.8\,\mathrm{GeV}$) for the track matched with the segment in the barrel (rear) muon chambers. For the track matched with the m.i.p. CAL cluster the cut $p > 1\,\mathrm{GeV}$ was used. A cut on the muon polar angle $30^\circ < \theta < 160^\circ$ was also applied for muons identified in the muon chambers. The muon identification and reconstruction efficiencies were estimated separately for muons reconstructed in the BMUON, RMUON and CAL using an independent sample of di-muon events.

The J/ψ rapidity in the laboratory frame [1], defined as $Y_{\mathrm{lab}} = {}^1\!/\!_2 \ln[(E_\psi + p_{Z,\psi})/(E_\psi - p_{Z,\psi})]$, was limited to a region of good acceptance $-1.6 < Y_{\mathrm{lab}} < 1.3$.

The inelasticty of J/ψ was restricted to the range $0.2 < z < 0.9$. The lower z cut removes the region of high non-resonant background due to fake muons and the upper z cut removes elastic and suppresses proton dissociative events. In order to further suppress the proton dissociative admixture the following cuts were applied:

- the analysis was restricted to events with an energy deposit greater than 1 GeV in a cone of 35° along the outgoing proton direction (excluding calorimeter deposits due to the decay muons);
- in addition to the tracks associated to the two muons and the track associated to the scattered lepton, the event was required to have at least one track.

To estimate the remaining admixture from proton-dissociative events, the inelasticity distribution in data was fitted to a sum of inelastic (EPJPSI) and diffractive (EPSOFT) Monte Carlo (MC) predictions. The proton-dissociative contribution of $5 \pm 1\%$ was found and subtracted according to the EPSOFT predictions.

Monte Carlo studies showed that the contribution from beauty decays is small, hence no implicit subtraction was done. The background from ψ' cascade decays is expected to be 15% [10, 23]; this contribution was not subtracted from the measured cross sections.

Acceptance, resolution and efficiency corrections are applied to the data using simulated MC events, with all generated events being passed through the same reconstruction chain as the data. The Monte Carlo generator used for inelastic J/ψ production is EPJPSI [24]

[1] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the "forward direction", and the X axis pointing left towards the centre of HERA. The coordinate origin is at the nominal interaction point. In the γp centre-of-mass frame the photon direction was chosen to be the "forward direction".

which incorporates the LO matrix elements of the photon-gluon fusion process and the colour singlet model. Higher-order QCD effects are simulated through initial- and final-state parton showers. In EPJPSI hadronisation is done according to the Lund string model [25]. The proton diffractive dissociation admixture was simulated using the EPSOFT MC generator [26], which has been tuned to describe such processes at HERA [27].

The total invariant mass spectrum obtained in the data after the selection is shown in Fig. 1. The number of signal J/ψ events in a given analysis bin was extracted by fitting the invariant mass distribution in the interval $2.4 < M_{\mu^+\mu^-} < 3.6\,\text{GeV}$ with a superposition of a "modified" Gaussian to describe the signal and a linear function to describe the non-resonant background. It was found that this functional form described well both data and MC signals. The "modified" Gaussian function had the following form:

$$\text{Gauss}^{\text{mod}} \propto \exp[-0.5 \cdot x^{1+1/(1+0.5 \cdot x)}],$$

where $x = |(M_{\mu^+\mu^-} - M_0)/\sigma|$. The signal width, σ, as well as the number of signal events were free parameters of the fit. The position of the Gaussian, M_0, was fixed from the overall fit to the data. Cross sections were computed as the number of signal events, reconstructed in a bin after subtraction of the diffractive admixture, divided by the Monte Carlo acceptance correction factor, the branching ratio and the integrated luminosity.

A study of possible sources of systematic uncertainties was carried out. The main sources of uncertainty are the shape of the Q^2 and p_T distributions of the MC model used for the acceptance correction and the subtraction of the diffractive admixture. Individual contributions were added in quadrature to determine the total systematic error for each bin.

3 Results

The J/ψ mesons were measured in the kinematic range $2 < Q^2 < 80\,\text{GeV}^2$, $50 < W < 250\,\text{GeV}$, $0.2 < z < 0.9$ and $-1.6 < Y_{\text{lab}} < 1.3$. In Fig. 2–3, the data are compared to predictions in the framework of NRQCD [28] and in the colour singlet model with k_T-factosization [29].

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 charm quark mass ($m_c = 1.5 \pm 0.1\,\text{GeV}$), renormalization 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 CS predictions are below but consistent both in shape and normalization with the data within the uncertainties shown. However, the differential cross sections as a function of transverse momentum squared in the laboratory system (p_T^2) and in the photon-proton centre-of-mass system (p_T^{*2}), which are too soft compared to the data. In photoproduction, it was found that NLO corrections were needed to describe the J/ψ transverse momentum spectrum in the framework of the CSM model.

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 the transverse momenta the predictions overshoot the data.

For the prediction within the k_T-factorisation approach (LZ(kt, CS)) only one of the uncertainty sources is presented, namely a variation of the pomeron intercept Δ which controls the normalization of the unintegrated gluon density used in the calculation in the form suggested by Blümlein [30]. 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 $m_c = 1.55\,\text{GeV}$. The renormalization and factorisation scales were set to the absolute value of the initial gluon transverse momentum. A calculation in the framework of the collinear factorisation within the CSM (LZ(CS)) was also provided [29] 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 normalization and shape. However, the predicted spectrum of transverse momentum in the photon-proton centre-of-mass system is softer than in the data. There is also an excess in the photon direction, i.e. at low values of the J/ψ rapidity in the laboratory system Y_{lab} and high values of the rapidity in the photon-proton centre-of-mass system Y^*.

4 Summary

Results on inelastic charmonium production in DIS have been obtained with the ZEUS detector and compared to calculations in the framework of NRQCD and the k_T-factorisation approach.

The LO colour singlet predictions, based on the collinear pQCD, 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 values of the transverse momenta agreement with the data is reasonable, but NLO corrections are needed to draw stronger conclusions. The calculation in k_T-factorisation approach within the colour singlet model gives an overall better description of the data.

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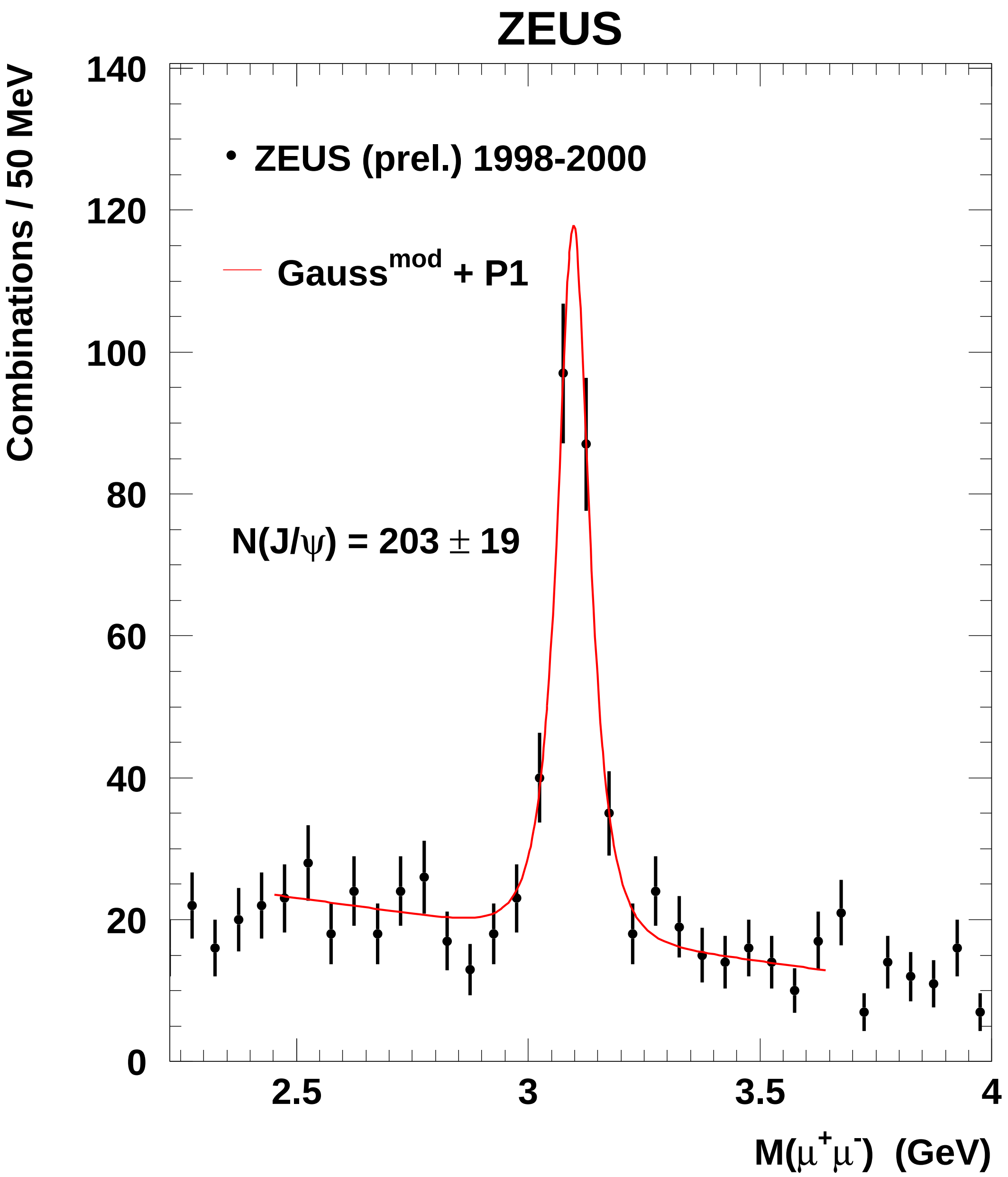

Figure 1: *Invariant mass spectrum after all selection cuts. The curve is the result of the fit with a modified Gaussian for the signal and a linear function (P1) for the non-resonant background.*

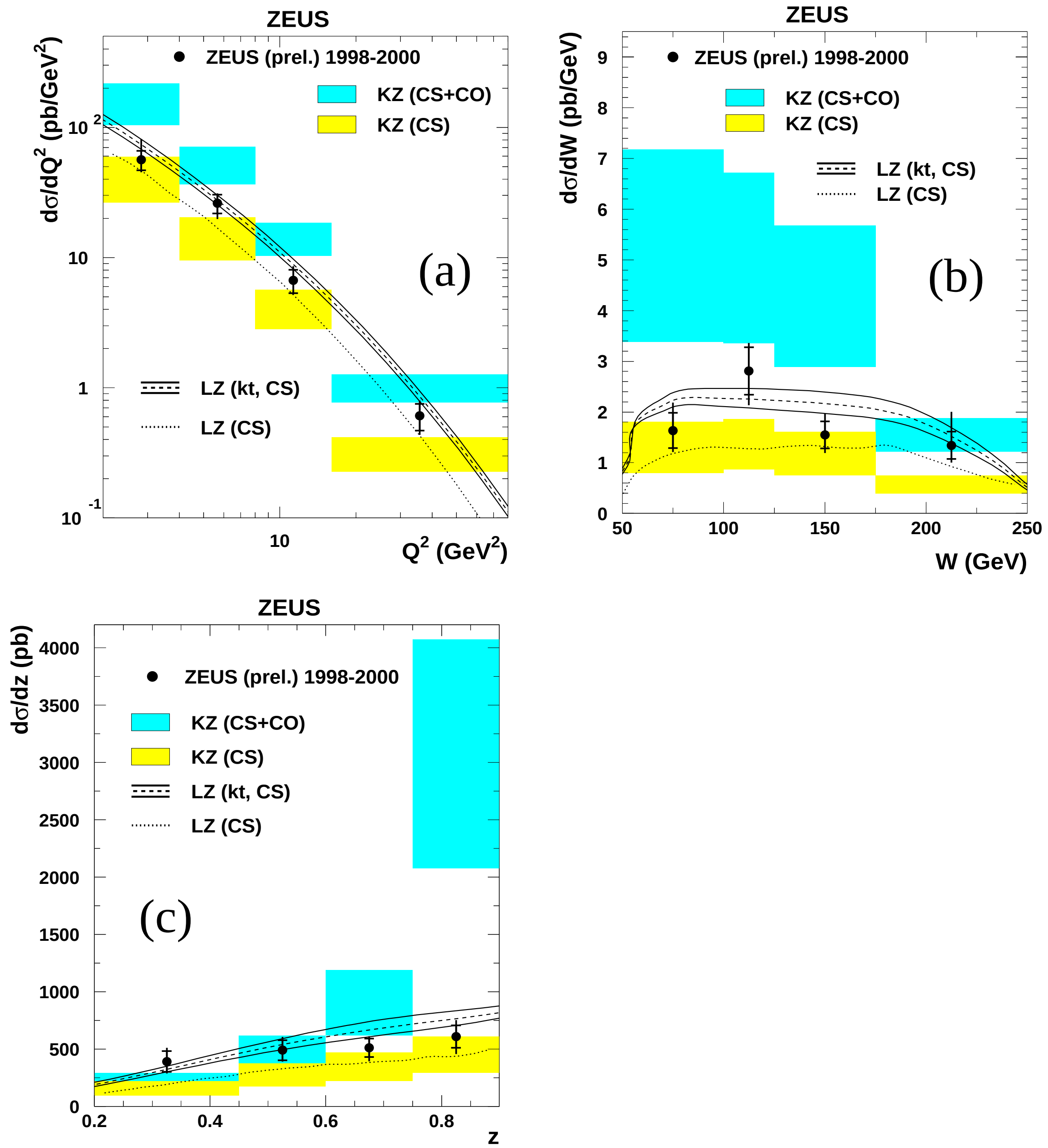

Figure 2: *Differential cross sections in the kinematic region $2 < Q^2 < 80\ GeV^2$, $50 < W < 250\ GeV$, $0.2 < z < 0.9$ and $-1.6 < Y_{lab} < 1.3$ as a function of (a) virtuality of the exchanged photon Q^2, (b) photon-proton centre-of-mass energy W and (c) inelasticity z. The inner error bars of the data points show the statistical uncertainty; the outer bars show statistical and systematic uncertainties added in quadrature. The data are compared to LO NRQCD predictions KZ(CS + CO) (upper band) and KZ(CS) (lower band) [28] and the calculation LZ(kt,CS) in k_T-factorisation approach within the CSM [29] (solid lines delimit the uncertainty, dashed line shows the central value). The CSM prediction LZ(CS) in the collinear factorisation by authors of [29] is also shown (dotted line).*

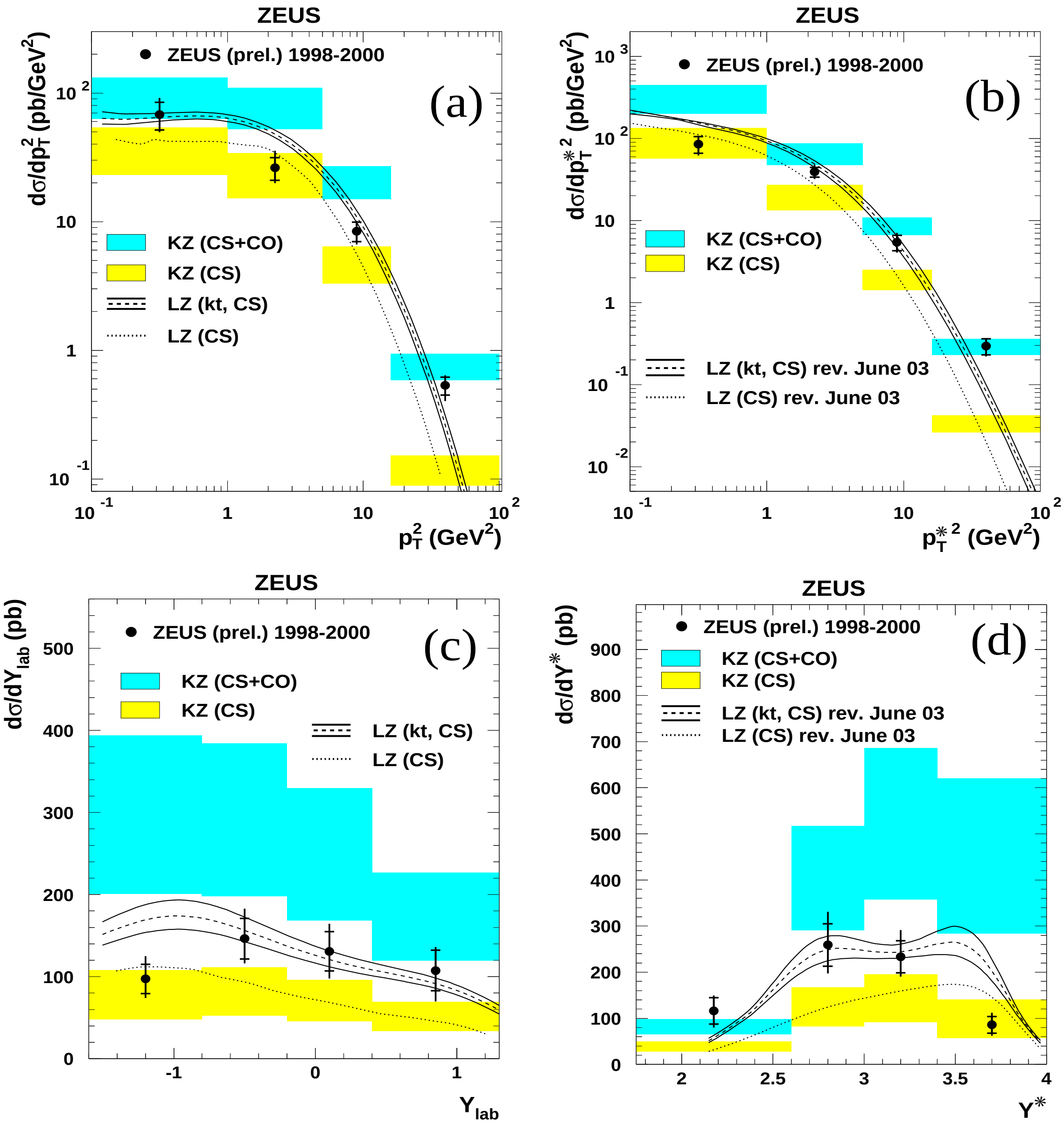

Figure 3: *Differential cross sections in the kinematic region $2 < Q^2 < 80\ GeV^2$, $50 < W < 250\ GeV$, $0.2 < z < 0.9$ and $-1.6 < Y_{lab} < 1.3$ as a function of J/ψ transverse momentum squared (a) in the laboratory system and (b) in the photon-proton centre-of-mass system, rapidity of J/ψ (c) in the laboratory and (d) γp centre-of-mass system. The inner error bars of the data points show the statistical uncertainty; the outer bars show statistical and systematic uncertainties added in quadrature. The data are compared to LO NRQCD predictions KZ(CS+CO) (upper band) and KZ(CS) (lower band) [28] and the calculation LZ(kt,CS) in k_T-factorisation approach within the CSM [29] (solid lines delimit the uncertainty, dashed line shows the central value). The CSM prediction LZ(CS) in the collinear factorisation by authors of [29] is also shown (dotted line).*