Submitted to the
International Europhysics Conference on High Energy Physics
17–23 July 2003, Aachen, Germany

Abstract: 569 **Parallel Session(s): HQCD, HP, HF**

Measurement of inelastic J/ψ helicity distributions at HERA

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Abstract

The decay angular distributions for inelastic photoproduction of J/ψ mesons have been measured in ep collisions with the ZEUS detector at HERA, using an integrated luminosity of 114 pb^{-1}. J/ψ mesons are identified using the decay mode $J/\psi \rightarrow \mu^+\mu^-$ and were measured in the range $50 < W < 180$ GeV , where W is the photon–proton centre–of–mass energy. The polar and azimuthal distributions of the μ^+ in the J/ψ rest frame are measured as a function of p_T, for $p_T > 1$ GeV and $z > 0.4$ and as function of z, for $p_t > 1$ GeV and $0.1 < z < 0.9$, where p_T is the transverse momentum of the J/ψ in the laboratory frame and z is the the fraction of the incident photon energy carried by the J/ψ in the proton rest frame. The experimental results are reasonably well described by the theoretical predictions at leading order.

1 Introduction

In the HERA photoproduction regime, where the virtuality of the exchanged photon is small, the production of inelastic J/ψ mesons arises mostly from direct and resolved photon interactions. In leading–order (LO) Quantum Chromodynamics (QCD), the two processes can be distinguished: in direct photon processes, the photon couples directly to a parton in the proton; in resolved photon processes, the photon acts as a source of partons, one of which participates in the hard interaction. Diffractive production, $\gamma p \to J/\psi N$, where N is a proton–dissociative state, contributes significantly to the inelastic production of J/ψ mesons by the direct photon process.

Direct and resolved photon cross sections can be calculated using perturbative QCD (pQCD) in the colour–singlet (CS) and colour–octet (CO) frameworks [1, 2]. In the CS model, the colourless $c\bar{c}$ pair produced by the hard subprocess is identified with the physical J/ψ state. In the CO model, the $c\bar{c}$ pair emerges from the hard process with quantum numbers different from those of the J/ψ and evolves into the physical J/ψ state by emitting one or more soft gluons.

The production of J/ψ mesons has been measured in $p\bar{p}$ collisions by the CDF collaboration [3, 4]. Predictions of the CS model, which for $p\bar{p}$ collisions exist only at LO in QCD, underestimate the data by factors of between 10 and 80. However, after adjustment of the corresponding matrix elements, this difference can be accounted for by the CO contributions [5, 6, 7]. Currently, the matrix elements governing the strength of this process cannot be calculated, but have to be determined from experiment.

The various J/ψ photoproduction processes can be distinguished using the inelasticity variable, z, defined as:

$$z = \frac{P \cdot p_{J/\psi}}{P \cdot q}, \tag{1}$$

where P, $p_{J/\psi}$ and q are the four–momenta of the incoming proton, the J/ψ meson and the exchanged photon. In the proton rest frame, z is the fraction of the photon energy carried by the J/ψ. Previous HERA data [8, 9] have shown that the diffractive process populates the high-z region, $z > 0.9$. The direct and resolved photon processes are expected to dominate in the regions $0.2 \lesssim z < 0.9$ and $z \lesssim 0.2$, respectively [1].

The J/ψ helicity distributions, namely the polar and azimuthal distribution of the J/ψ decay leptons in the J/ψ rest frame, are predicted, by the CS and CO models, to have a different dependence on the transverse momentum p_T and the z of the J/ψ. Furthermore, helicity studies are mainly shape measurements; consequently they are less sensitive to the choice of the non perturbative QCD input parameters, such as the charm quark mass, m_c, or the QCD scale parameter Λ, compared with measurements of differential cross sections. Results from the CDF collaboration [10] show some discrepancies between the helicity measurements and predictions [2] using CO matrix elements extracted from the CDF cross section data.

Since the matrix elements are expected to be universal, the analysis of the HERA J/ψ helicity distributions constitutes a stringent test of the CS and CO models. Helicity measurements have already been performed by the H1 [9] and ZEUS [8] collaborations.

Within the experimental and theoretical uncertainties, both the CS and CO predictions have been found to fit the data reasonably well. In this study the statistics of the previous ZEUS analysis [8] is summed with the data collected in the years from 1998 to 2000. This corresponds to an increase in statistics of a factor 3 with respect to the previous analysis.

2 Data Analysis

In this study J/ψ mesons were identified using the decay mode $J/\psi \to \mu^+\mu^-$ and were measured in the range $50 < W < 180$ GeV, where W is the γp centre–of–mass energy. Due to the requirement of an energy deposit in the outgoing proton direction the final sample contains inelastic J/ψ events from direct and resolved photon processes and proton diffractive J/ψ events at high M_N, where M_N is the mass of the proton dissociative state. The elastic component, $\gamma p \to J/\psi p$, is removed completely.

The polar and azimuthal distributions of the μ^+ in the J/ψ rest frame have been measured as a function of p_T, for $p_T > 1$ GeV and $z > 0.4$, and as a function of z, for $p_T > 1$ GeV and $0.1 < z < 0.9$ and compared to leading–order QCD predictions.

The data presented here were collected in the years 1996–2000 and correspond to a total integrated luminosity of 114 ± 3 pb^{-1}. HERA operated with electrons or positrons of 27.5 GeV. The proton beam energy was 820 GeV before 1998 and 920 GeV since.

The trigger selection, analysis cuts and kinematic variables reconstruction were performed as in previous analyses [8]. The MC samples used in the analysis have been generated and processed as previously [8].

The helicity analysis was performed in the so called target frame, where the quantisation axis, z axis, is chosen along the opposite of the incoming proton direction in the J/ψ rest frame. The polar angle, $\theta^\star$, is defined as the angle between the μ^+ vector in the J/ψ rest frame and the quantisation axis. To define the azimuthal vector, $\varphi^\star$, at least another axis is necessary, chosen, according to the prescriptions of [2], along the vector $\vec{p}_\gamma \times (-\vec{p}_p)$ in the J/ψ rest frame, y axis. The third axis, x axis, is chosen to complete a right–handed coordinate system in the J/ψ rest frame.

With these definitions the decay angular distribution in the J/ψ rest frame can be parametrised as:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega^\star dy} \propto 1 + \lambda(y)\cos^2\theta^\star + \mu(y)\sin 2\theta^\star \cos\varphi^\star + \frac{\nu(y)}{2}\sin^2\theta^\star \cos 2\varphi^\star \tag{2}$$

where the variable y can be either the p_T or the inelasticity z of the J/ψ. Integrating in $\varphi^\star$ the angular distribution becomes:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^\star dy} \propto 1 + \lambda(y)\cos^2\theta^\star, \tag{3}$$

while integrating in $\theta^\star$:

$$\frac{1}{\sigma}\frac{d\sigma}{d\varphi^\star dy} \propto 1 + \frac{\lambda(y)}{3} + \frac{\nu(y)}{3}\cos 2\varphi^\star. \qquad (4)$$

The parameter λ was determined by reweighting the HERWIG MC $dN/d\cos\theta^\star$ generator level distribution according to Eq. 3 for different values of λ. The χ^2 for the $dN/d|\cos\theta^\star|$ distribution in data and MC was then calculated for each value of λ in the MC and the minimum χ^2 gave the central value of λ. For the analysis as a function of p_T the procedure was repeated for each p_T bin in the range $1 < p_T < 5$ GeV. The p_T bins have been chosen to have almost the same number of J/ψ events in each bin, except for the last one. The systematic uncertainties [8] were negligible with respect to the error determined from the χ^2 fit. The z integration range was set [2] to $0.4 < z < 1$. A significant fraction of diffractive events is present in this range which falls with increasing p_T. No reliable theoretical prediction for the helicity of the diffractive production channel is currently available. The result is shown in Fig. 1 (a); where here and in the following the error bars correspond to the total experimental uncertainties, the dominant experimental uncertainty is statistical. These new preliminary ZEUS data points are in good agreement with the previously published ZEUS helicity studies [8]. For the analysis as a function of z, the procedure was repeated for each z bin in the range $0.1 < z < 0.9$ with the additional requirement $p_T > 1$ GeV. The result is shown in Fig. 1 (b). The uncertainty increases to low z because the number of events is small and because the signal over background ratio worsens. These are also the reasons why the z range $0.1 < z < 0.4$ was excluded for the analysis versus p_T. The diffractive contamination decreases with decreasing z values. In Fig. 1 the ZEUS data points are compared with the H1 measurements [9]. The band in Fig. 1, identified by the label BKV (LO, CS+CO), shows the LO prediction [2] including both CS and CO terms, the spread is due to theoretical uncertainties in the values of the CO matrix elements. The dashed line, identified by the label BKV (LO, CS), shows the corresponding prediction in the restricted CS framework.

The measurement of the parameter ν proceeds as described for λ, ν was determined by reweighting the HERWIG MC $dN/d\varphi^\star$ generator level distribution according to Eq. 4 for different values of ν. The χ^2 for the $dN/d\varphi^\star$ distribution in data and MC was then calculated for each value of ν in the MC and the minimum χ^2 gave the central value of ν. The same p_T and z selections and bins used for the λ analysis have been used for the extraction of the parameter ν. The results as a function of the p_T and of the z variables are shown in Fig. 2 (a) and (b), respectively. In Fig. 2 the data are compared with the recent H1 measurements [9]. The band in Fig. 2, identified by the label BKV (LO, CS+CO), shows the LO prediction of [2] including both CS and CO terms; the spread is due to theoretical uncertainties in the values of the CO matrix elements. The dashed line, identified by the label BKV (LO, CS), shows the corresponding prediction in the restricted CS framework. All data points are systematically below the prediction. Using the ZEUS data only, a χ^2 test gives a χ^2/n.d.f. of 1.94 for 7 n.d.f., Fig. 2 (a), and a χ^2/n.d.f. of 2.71 for 5 n.d.f., Fig. 2 (b).

3 Conclusions

The inelastic J/ψ helicity distributions in the photoproduction regime have been measured and compared to leading–order QCD predictions in both CS and CO frameworks. In particular the helicity parameters λ and ν have been analysed, in the target frame, as a function of the J/ψ p_T and inelasticity, z. Within the experimental and theoretical errors both the CS and CO predictions have been found to fit the data reasonably well but from the analysis of the azimuthal distributions the ZEUS data seem to disfavor the colour singlet only picture. Applying a χ^2 test to the colour singlet only prediction for the parameter ν as a function of z a χ^2/n.d.f. value of 2.71 for 5 n.d.f. is found, this test however neglects an unknown theoretical uncertainty due to higher order corrections. As the helicity measurements are mainly shape measurements, higher–order corrections are not expected to change the theoretical picture very significantly. An explicit NLO calculation is however required to quantify the theoretical uncertainty [11].

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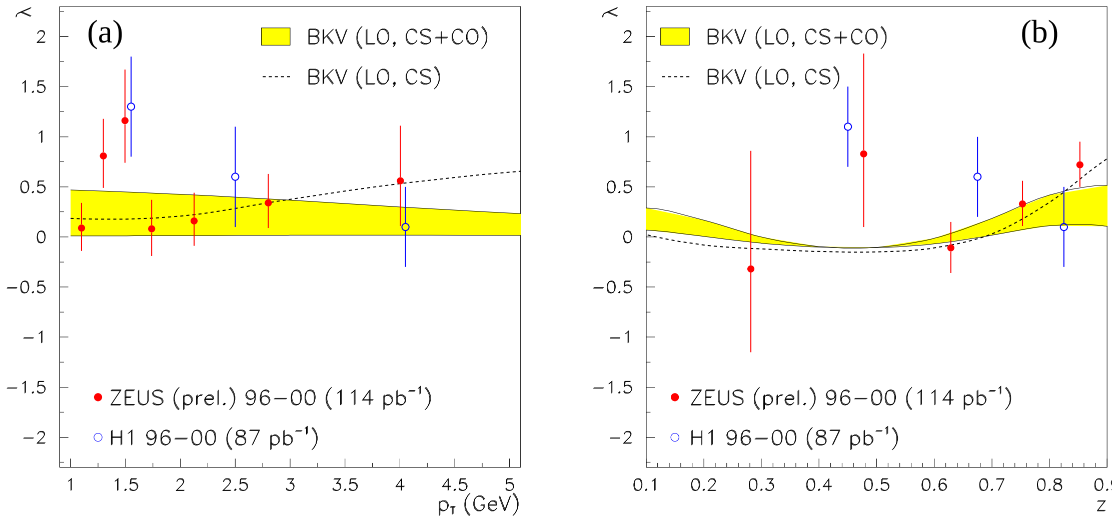

Figure 1: Distribution of the helicity parameter λ as a function of p_T, Fig. (a), and z, Fig. (b). The error bars correspond to the total experimental uncertainties. The theoretical curves are described in the text.

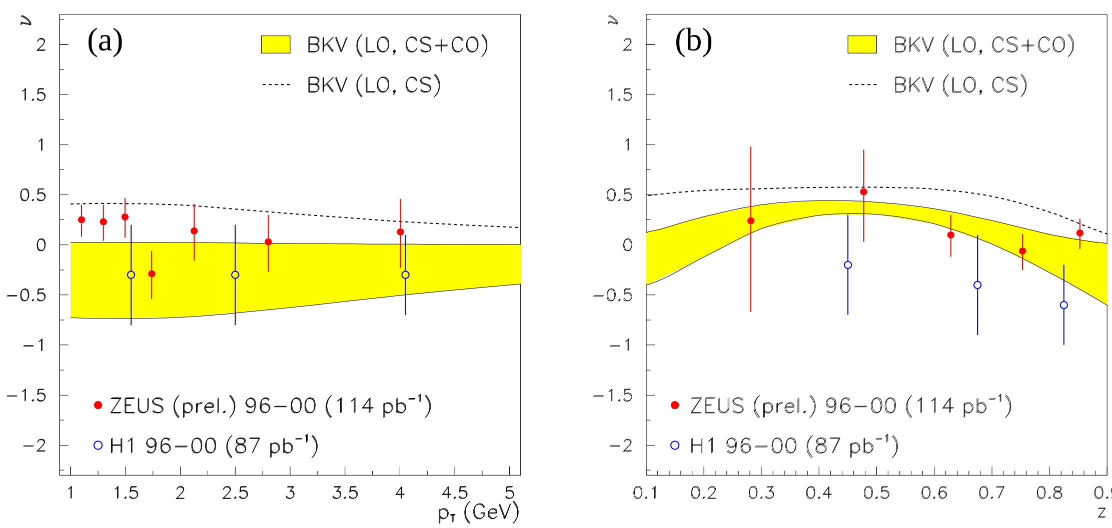

Figure 2: Distribution of the helicity parameter ν as a function of p_T, Fig. (a), and z, Fig. (b). The error bars correspond to the total experimental uncertainties. The theoretical curves are described in the text.