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Measurement of J/ψ helicity distributions in inelastic photoproduction at HERA

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Abstract

The decay angular distributions for inelastic photoproduction of J/ψ mesons are measured in ep collisions with the ZEUS detector at HERA, using an integrated luminosity of 241 pb^{-1} collected between 1996 and 2000 (HERA I data) and between 2004 and 2005 (HERA II data). J/ψ mesons are identified using the decay mode $J/\psi \to \mu^+\mu^-$ and are 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 compared to 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, 3]. 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 [4, 5]. Predictions of the CS model, which for $p\bar{p}$ collisions exist only at LO in QCD, have been found to 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 [6, 7, 8]. Currently, the matrix elements governing the strength of this process cannot be calculated, but have to be determined from experiment. HERA inelastic J/ψ differential cross section measurements [9, 10] are reasonably well described by LO CS plus CO calculations with CO contributions as determined from $p\bar{p}$ data although the calculations are affected by large theoretical uncertainties; the photoproduction data are also reproduced by a NLO calculation performed in the restricted CS framework.

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. Analyses of previous HERA data [9, 10] 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 [2].

Study of the J/ψ helicity distributions, namely the polar and azimuthal distributions of the J/ψ decay leptons in the J/ψ rest frame, may allow distinction between the CS and CO models, since the predicted dependence of the helicity parameters on the transverse momentum p_T and the z of the J/ψ is found to be different. 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 [11] show some discrepancies between the helicity measurements and predictions [3] using CO matrix elements extracted from the CDF cross section data.

Since the matrix elements describing the transition between the $c\bar{c}$ pair produced at the end of the hard subprocess and the J/ψ state 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 distribution measurements have already been performed by the ZEUS [9, 12] and H1 [10] collaborations.

In this study we use the data collected in the years from 1996 to 2000 (HERA I) and from 2004 to 2005 (HERA II). This corresponds to an increase in statistics of a factor of six with respect to the published ZEUS analysis [9] and of two with respect to the preliminary ZEUS analysis [12].

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, corresponding to a total integrated luminosity of 114 ± 3 pb^{-1}, and in the years 2004–2005, corresponding to a total integrated luminosity of 127 ± 4.4 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 [9]. The MC samples used in the analysis have been generated and processed as described previously [9].

The helicity analysis was performed in the so called target frame defined as the J/ψ rest frame with the quantisation axis (z') 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 (y') is necessary, chosen, according to the prescriptions of [3], along the vector $\vec{p}_\gamma \times (-\vec{p}_p)$ in the J/ψ rest frame. The third axis (x') is chosen to complete a right–handed coordinate system in the J/ψ rest frame.

With these definitions and as shown in [3] the decay angular distribution in the J/ψ rest frame can be parametrised as:

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

where the symbolic variable y is a shorthand for either the p_T or the inelasticity z of the J/ψ. After integrating $\varphi^\star$ 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 $\cos\theta^\star$ results in:

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

The parameter λ is 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 obtained from comparing the measured $dN/d|\cos\theta^\star|$ distribution to the MC is calculated for each value of λ in the MC and the minimum χ^2 gives the central value of λ. For the analysis as a function of p_T the procedure is repeated for each p_T bin in the range $1 < p_T < 10$ GeV. The p_T bins are chosen to have almost the same number of J/ψ events in each bin, except for the last two. The z integration range is set [3] to $0.4 < z < 1$. The systematic uncertainties [9] are negligible with respect to the error determined from the χ^2 fit. 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. For the analysis as a function of z, the procedure is 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. The band in Fig. 1, identified by the label BKV (LO, CS+CO), shows the LO prediction [3] 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; it is 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 obtained from comparing the measured $dN/d\varphi^\star$ distribution to the MC is calculated for each value of ν in the MC and the minimum χ^2 gives the central value of ν. The same p_T and z selections and bins used for the λ analysis are 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. The band in Fig. 2, identified by the label BKV (LO, CS+CO), shows the LO prediction of [3] 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.

A fraction of diffractive events is present at high z and low p_T; this contamination decreases as z decreases and p_T increases. No reliable theoretical prediction for the helicity of the diffractive production channel is currently available. To study the sensitivity of the results to the diffractive background the following tests have been performed:

- the z integration range was changed from $0.4 < z < 1$ to $0.4 < z < 0.9$; the requirement $z < 0.9$ is known to strongly suppress the diffractive background [9];
- at least three tracks from the primary vertex, the two muons coming from the J/ψ decay and one additional track, were required for each event; this reduces the efficiency for the signal but removes almost completely the diffractive background [13].

The observed changes in the central values of the helicity parameters λ and ν are found to be small compared to the present experimental uncertainty.

These new preliminary ZEUS data points are in good agreement with the previously published ZEUS helicity studies [9] and [12]. The analysis of the parameter ν as a function of the z variable, Fig. 2 (b), shows that almost all the data points are systematically below the LO CS prediction, this trend was already seen in [12] but is confirmed with increased statistics. The data points instead favour the LO CS+CO prediction. This suggest that the naive CS picture does not fully describe all aspect of HERA inelastic J/ψ data and shows the relevance of the CO terms. In order to make stronger conclusions more data and improved theoretical calculations would be relevant even if higher–order corrections are not expected to change the theoretical picture very significantly [14].

3 Conclusions

The J/ψ helicity distributions in inelastic photoproduction have been measured and compared to leading–order QCD predictions in both CS and CO frameworks. 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. This conclusion comes from the analysis of the parameter ν as a function of z and p_T, in this case ZEUS data are better described by a LO theoretical calculation taking care of CS and CO contributions. This trend has been confirmed and made stronger by the increased statistics available with respect to the previous ZEUS preliminary result. An explicit NLO calculation is however required to quantify the theoretical uncertainty even if the helicity measurements, being mainly shape measurements, are not expected to be very sensitive to higher–order corrections.

References

[1] N. Brambilla et al., CERN Yellow Report, CERN-2005-005, Geneva.

[2] M. Krämer, Prog. Part. Nucl. Phys., **47**, 141 (2001).

[3] M. Beneke, M. Krämer and M. Vanttinen, Phys. Rev. **D 57**, 4258 (1998).

[4] CDF Collab., F. Abe et al., Phys. Rev. Lett. **79**, 572 (1997).

[5] CDF Collab., F. Abe et al., Phys. Rev. Lett. **79**, 578 (1997).

[6] M. Cacciari and M. Krämer, Phys. Rev. Lett. **76**, 4128 (1996).

[7] P. Ko, J. Lee and H. S. Song, Phys. Rev. **D 54**, 4312 (1996).

[8] P. Ko, J. Lee and H. S. Song, Phys. Rev. **D 60**, 119902 (1999).

[9] ZEUS Collab., J. Breitweg et al., Z. Phys. **C 76**, 599 (1997);
ZEUS Collab., S. Chekanov et al., Eur. Phys. J. **C 27**, 173 (2002).

[10] H1 Collab., S. Aid et al., Nucl. Phys. **B 472**, 3 (1996);
H1 Collab., C. Adloff et al., Eur. Phys. J. **C 25**, 25 (2002).

[11] CDF Collab., T. Affolder et al., Phys. Rev. Lett. **85**, 2886 (2000).

[12] ZEUS Collab., S. Chekanov et al., abstract 569, EPS03, 17–23 July 2003, Aachen (Germany).

[13] ZEUS Collab., S. Chekanov et al., Eur. Phys. J. **C 44**, 13 (2005).

[14] M. Krämer, private communication.

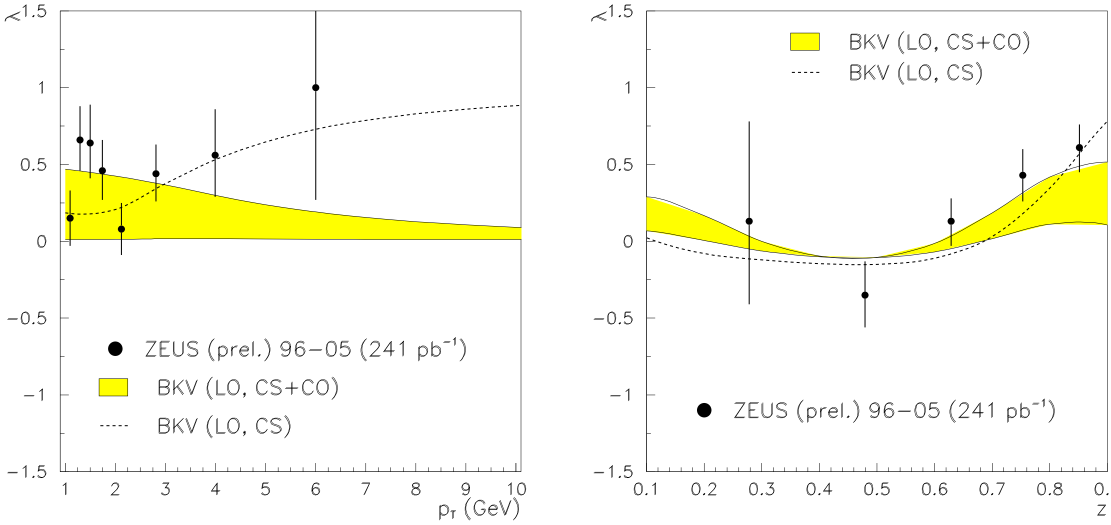

Figure 1: Distribution of the helicity parameter λ as a function of p_T, Fig. (a), and z, Fig. (b). The error bars correspond to the total experimental uncertainties. The theoretical curves are described in the text.

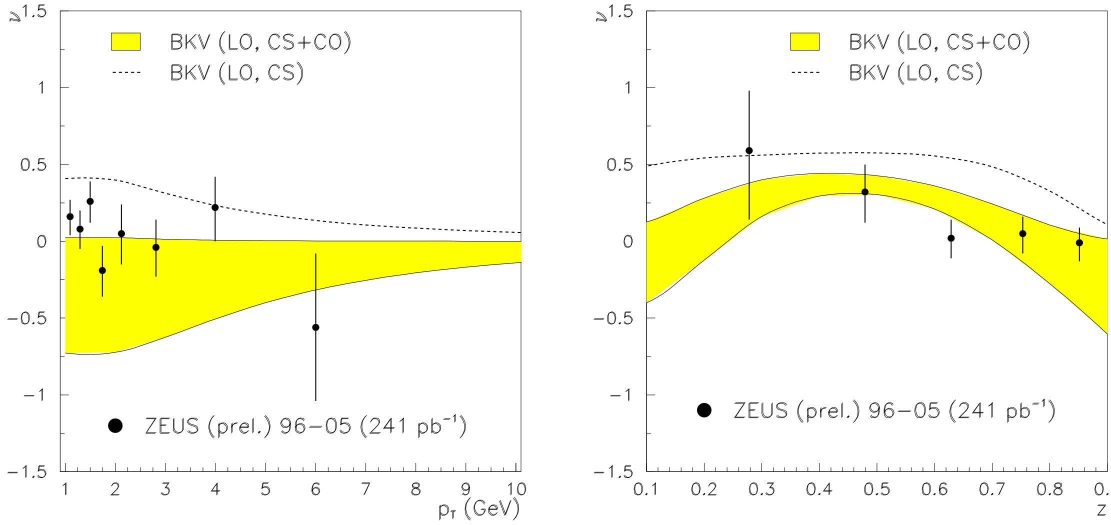

Figure 2: Distribution of the helicity parameter ν as a function of p_T, Fig. (a), and z, Fig. (b). The error bars correspond to the total experimental uncertainties. The theoretical curves are described in the text.