Inelastic $J/\psi$ helicity distributions

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The $J/\psi$ decay angular distributions have been measured in inelastic photoproduction in $ep$ collisions with the ZEUS detector at HERA, using an integrated luminosity of 468 pb$^{-1}$. The range in photon-proton centre-of-mass energy, $W$, was $50 < W < 180$ GeV. The $J/\psi$ mesons were identified through their decay into muon pairs. The polar and azimuthal angles of the $\mu^+$ were measured in the $J/\psi$ rest frame and compared to theoretical predictions at leading and next-to-leading order in QCD.

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1. Introduction

In the HERA photoproduction regime, where the virtuality of the exchanged photon is small, the production of inelastic \( J/\psi \) mesons is dominated by boson-gluon fusion: a photon emitted from the incoming lepton interacts with a gluon coming from the proton to produce a \( c\bar{c} \) pair which subsequently forms a \( J/\psi \) meson. Production of \( J/\psi \) through boson-gluon fusion can be calculated using perturbative Quantum Chromodynamics (pQCD) in the colour-singlet (CS), in the non-relativistic QCD (NRQCD) and in the \( k_T \)-factorisation frameworks.

In the CS approach, only the colourless \( c\bar{c} \) pair produced in the hard subprocess can lead to a physical \( J/\psi \) state. In the NRQCD approach, a \( c\bar{c} \) pair emerging from the hard process in a colour-octet (CO) state can also evolve into a \( J/\psi \) state with a probability proportional to universal long-distance matrix elements (LDME) that are obtained from experiment. In the \( k_T \)-factorisation approach, the effects of non-zero transverse momentum of the incoming parton are taken into account. Cross sections are then calculated in the CS approach as a convolution of unintegrated (transverse-momentum dependent) parton densities and leading-order (LO) off-shell matrix elements.

The polar and azimuthal distributions of the \( J/\psi \) decay leptons in the \( J/\psi \) rest frame, the helicity distributions, may be used to distinguish between CS and CO models [1]. Helicity distribution measurements have already been performed by the ZEUS [2] and H1 [3, 4] collaborations. The data sample of this study [5] includes the data used in the previously published ZEUS analysis [2] and corresponds to an increase in statistics of a factor of 12.

2. Data analysis

\( J/\psi \) mesons were identified using the decay mode \( J/\psi \to \mu^+\mu^- \). The online and offline selections as well as the reconstruction of the kinematic variables closely follow a previous analysis [2]. The transverse momentum, \( p_T \), of the \( J/\psi \) candidate was required to be larger than 1 GeV. The photon-proton centre-of-mass energy \( W \) was restricted to the range \( 50 < W < 180 \) GeV. In addition, events were required to have an energy deposit larger than 1 GeV in a cone of 35° around the forward direction (excluding possible calorimeter deposits due to the decay muons). According to Monte Carlo (MC) simulations, these requirements completely reject exclusively produced \( J/\psi \) mesons (\( ep \to epJ/\psi \)) as well as proton-diffractive events (\( ep \to eYJ/\psi \)) in which the mass of the proton dissociative state, \( M_Y \), is below 4.4 GeV. To further reduce diffractive background, events were also required to have at least one additional track with a transverse momentum larger than 0.125 GeV and pseudorapidity \( |\eta| < 1.75 \).

The following other sources of \( J/\psi \) mesons, which were classified as background in the present analysis, were estimated either from MC models or previous measurements:

- **dissociative production of \( J/\psi \) mesons with proton dissociation:** the overall contribution of this background is 6%; it is largest in the lowest \( p_T \) bin (1 ≤ \( p_T \) ≤ 1.4 GeV), where it is 7.5%, and in the highest \( z \) bin (0.9 ≤ \( z \) ≤ 1), where it is 66%;

- **\( J/\psi \) mesons originating from \( B \)-meson decays:** 1.6% of the observed \( J/\psi \) events were from \( B \)-meson decays; the fraction is largest in the highest \( p_T \) bin (4.2 ≤ \( p_T \) ≤ 10 GeV), where it is equal to 6.3%, and in the lowest \( z \) bin (0.1 ≤ \( z \) ≤ 0.4), where it is 8.4%
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- J/ψ from ψ' decays: this contribution is expected to be around 15%, as obtained using the direct measurement of the ψ' to J/ψ cross section ratio [2] and the branching ratio of the ψ' to J/ψ.

Although the relative rate of each process could be estimated, the helicity distributions of these J/ψ sources are poorly known, so these contributions were not subtracted.

The helicity analysis was performed in the so-called “target frame” [1]. The polar and azimuthal angles of the µ+ in this frame are denoted θ* and φ*. The differential cross sections in θ* and φ* can be parametrised as [1]:

\[
\frac{d\sigma}{d\cos\theta^*} \propto 1 + \lambda \cos^2\theta^*,
\]

(2.1)

\[
\frac{d\sigma}{d\phi^*} \propto 1 + \frac{\lambda}{3} + \frac{\nu}{3} \cos 2\phi^*,
\]

(2.2)

where λ and ν, the polar and azimuthal angular parameters, are functions of p_T and z. The λ and ν parameters were determined in bins of z and p_T, each time integrating over the other variable. As a function of p_T, the integration range for z was set to 0.4 < z < 1, thereby avoiding the region 0.1 < z < 0.4 where the ratio of signal to combinatorial background is rather poor. The integration range in p_T started at p_T = 1 GeV.

The HERWIG MC generator-level distributions dN/dcosθ* (dN/dφ*) were re-weighted according to Eq. 2.1 (2.2) within a search grid of λ (ν) values. For each re-weighted distribution, the value of \( \chi^2 \) was calculated from a comparison to the data. The λ (ν) value providing the minimum \( \chi^2 \), \( \chi^2_{\text{min}} \), was taken as the central value. The parameter values with \( \chi^2 = \chi^2_{\text{min}} + 1 \) were used to calculate the statistical uncertainties. Equation 2.1 was first used to extract λ, and then λ was inserted into Eq. 2.2 to extract ν.

3. Results

The values of the parameter λ are shown as a function of p_T and z in Figs. 1a) and b), respectively; the values of the parameter ν are displayed in Figs. 2a) and b).

The data are compared to various theoretical predictions for photoproduction, at \( Q^2 = 0 \). These predictions do not consider the polarisation due to J/ψ coming from ψ' decays, B-meson decays and from diffractive processes. The curves identified by the label LO CS show the LO prediction in the CS framework including both direct and resolved processes. The two lines identified by the label LO + k_T (JB) and LO + k_T (dGRV), represent the predictions of a k_T-factorisation model using two different unintegrated gluon distributions and including only direct processes. The band identified by the label NLO CS represents the predictions of a NLO calculation including only direct processes. The width of the band gives the uncertainties of the calculation due to variations of the renormalisation and factorisation scales. It stops at z = 0.9 because no reliable predictions can be obtained near z = 1 for this fixed-order calculation. The band identified by the label LO CS+CO shows a LO prediction including direct and resolved processes in the NRQCD approach.

\[1\] In these resolved processes, the incoming photon does not couple to the c quark directly, but via its hadronic component. They are expected to contribute mainly to the region of z < 0.4.
and hence involving CS plus CO states. The width of the band results from the uncertainties in the values of the CO matrix elements. In Figs. 1a) and 2a), with $z$ integrated up to $z = 1$, the LO CS+CO cross section is CO dominated.

The NLO CS calculation for $p_T > 1$ GeV suffers from large scale uncertainties. In order to avoid this problem, measurements and calculations were repeated increasing the $p_T$ cut first to 2 GeV and then to 3 GeV. In Figs. 3a) and b) the $\lambda$ and $\nu$ parameters, respectively, are shown as a function of $z$ for $p_T > 2$ GeV, while in Figs. 3c) and d) the same parameters are displayed for $p_T > 3$ GeV. The NLO CS calculation, also shown in these figures, has now smaller uncertainties, but the agreement with the data is only satisfactory for the $\nu$ parameter. Sizeable discrepancies remain for the $\lambda$ parameter both for $p_T > 2$ GeV and $p_T > 3$ GeV.

4. Conclusions

The $J/\psi$ helicity distributions in the inelastic photoproduction regime have been measured using a luminosity of 468 pb$^{-1}$. The $J/\psi$ helicity parameters $\lambda$ and $\nu$ were extracted in the target frame as a function of the transverse momentum and of the inelasticity of the $J/\psi$. The results were compared to LO QCD predictions in the colour-singlet, colour-singlet plus colour-octet and $k_T$ factorisation frameworks. A recent NLO QCD prediction in the colour-singlet framework was also considered. Even though the experimental and theoretical uncertainties are large, none of the predictions can describe all aspects of the data.

References

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Figure 2: The helicity parameter $\nu$, measured in the target frame, as a function of (a) $p_T$, and (b) $z$. The measurement is performed in the kinematic range $50 < W < 180$ GeV, $0.1 < z < 1$ and $p_T > 1$ GeV. The measurement as a function of $p_T$ is restricted to the kinematic range $0.4 < z < 1$. The inner (outer) error bars correspond to the statistical (total) uncertainty. The theoretical curves are described in the text.

Figure 3: Distributions of the helicity parameters (a), (c) \( \lambda \) and (b), (d) \( \nu \) as a function of \( z \), measured in the target frame, for \( 50 < W < 180 \) GeV, \( 0.1 < z < 0.9 \) and (a), (b) \( p_T > 2 \) GeV and (c), (d) \( p_T > 3 \) GeV. The inner (outer) error bars correspond to the statistical (total) uncertainty. The theoretical bands are described in the text.