Measurement of the J/ψ helicity at ZEUS

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This article reviews the recent experimental results obtained by the ZEUS Collaboration in the study of the decay angular distributions for inelastic photoproduction of J/ψ in ep collisions at HERA. Emphasis will be placed on the comparison between data and theoretical developments in the quarkonium production field.

1 Introduction

The production of heavy quarkonia in high energy ep collisions provides an ideal and to some extent unique laboratory where our understanding of nonperturbative QCD and its interplay with perturbative QCD may be tested in a controlled framework. In the following, firstly we give a brief summary of the theory, then we show the measurements of the J/ψ helicity made by the ZEUS Collaboration, compared to theoretical predictions at leading order, and finally we give conclusions.

2 The theoretical framework

In ep collisions charmonium can be produced inelastically both through direct photon and resolved photon processes^a. In direct photon processes, the photon couples directly to a parton in the proton, whereas in resolved photon processes, the photon acts as a source of partons, one of which participates in the hard interaction. The charmonium state can emerge from the hard interaction either immediately with the right values of spin, angular momentum and colour, **colour singlet (CS) model**, or in a coloured $c\bar{c}$ state, **colour octet (CO) model**, which is followed by a long-distance transition to charmonium and light hadrons. This transition is parameterised through process-independent matrix elements, whose values are extracted from experimental data. The theory, incorporating in a coherent manner CS and CO terms, is called Non-Relativistic QCD (NRQCD). Despite these developments the range of applicability of these approaches to the practical case of charmonium is still subject of debate, as is the quantitative verification of factorisation between hard cross sections and matrix elements. The problematic aspect is that, because the charmonium mass is still not very large with respect to the QCD scale, non-factorisable corrections may not be suppressed enough. If the quarkonium is not part of an isolated jet, the expansions in NRQCD may not converge very well. Apart from the previous models, there is also the k_t -factorisation method which, starting from the CS model, uses k_t factorisation in an attempt to take into account initial-state radiation through parton distributions that depend on the parton's transverse momentum k_t , as well as on parton's longitudinal momentum fraction x . It generally gives answers that are very different from those of collinear factorisation. The k_t -dependent parton distributions are not very well known phenomenologically, and there are possibly unresolved theoretical issues, such as the universality of the k_t -dependent

^aExhaustive reviews of the theoretical situation regarding quarkonia production at high-energy colliders can be found in [1] and [2].

parton distributions. In this situation cross checks between various processes and predictions of different observables (for example quarkonium polarisation and differential cross sections) are crucial in order to assess the importance of different quarkonium production mechanisms, as well as the limitation of a particular theoretical approach. We have also to remember that NLO calculations exist only in photoproduction regime, restricted to the CS model. Within NRQCD and k_t frameworks the calculations are limited to leading order (LO) both in photoproduction and electroproduction regimes.

3 Helicity distributions

As said before, the motivation for considering the decay angular distributions (helicity distributions) of the J/ψ is to provide another observable (different from the differential cross sections) that can clarify the underlying production mechanism (CS vs. CO but also collinear vs. k_t factorisation). There are also various important advantageous aspects in analyzing helicity distributions. Their dependence on parameters that affect the absolute normalisation of cross sections, such as charm mass, strong coupling, renormalisation/factorisation scales and parton distribution parameters cancel to a large extent and do not constitute a significant uncertainty due to the fact that they are normalised distributions. The polarization measurements should not be affected, also, by the uncertainties and difficulties due to the necessary resummation in the endpoint region of the inelasticity variable z ^b ($z \rightarrow 1$) that may lead to a significant redistribution of $d\sigma/dz$ in z . From the experimental point of view, the only weak point is the necessity of large amount of statistics in order to determine with sufficient precision the helicity parameters, in other words one has to use both HERA-I and HERA-II data (for ZEUS this means an integrated luminosity of 470 pb⁻¹). The decay angular distribution in the J/ψ rest frame can be parametrised as:

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

where the angles θ and ϕ refer to the polar and azimuthal angles of the positive lepton from the J/ψ decay with respect to a coordinate system defined in the J/ψ rest frame, y stands for a set of variables (in the following the transverse momentum of the J/ψ , p_T , and z), the parameters λ, μ, ν are related to the density matrix elements and depend on the definition of the coordinate system. To determine the parameter λ one measures the decay angular distribution integrated over the azimuthal angle:

$$\frac{d^2\sigma}{d\theta dy} \propto 1 + \lambda(y) \cos^2 \theta \quad (2)$$

Then one measures the decay angular distribution integrated over the polar angle in order to determine ν :

$$\frac{d^2\sigma}{d\phi dy} \propto 1 + \frac{\lambda(y)}{3} + \frac{\nu(y)}{3} \cos 2\phi \quad (3)$$

The chosen frame is the so called “target frame” in which the quantization axis is taken to be the opposite of the incoming proton direction in the J/ψ rest frame. In Fig. 1 (a), the

^bThe inelasticity variable z is defined as $z = P \cdot p_\psi / P \cdot q$, where P, q, p_ψ are the 4-momenta of the incoming proton, incoming photon and outgoing J/ψ , respectively.

ZEUS data are shown (black points) for λ vs. p_T in the phase space region $0.4 < z < 0.9$ and $50 < W < 18 \text{ GeV}^c$ and in Fig. 1 (b) for λ vs. z in the phase space region $p_T > 1 \text{ GeV}$ and $50 < W < 180 \text{ GeV}$. The values $\lambda = -1$ and $\lambda = +1$ correspond to fully longitudinal and transverse polarization, respectively. The data are consistent with a trend towards transverse polarization with increasing p_T and z . The shaded band in the two figures is the prediction of a LO CS+CO calculation [3], the spread in the prediction is due to the theoretical uncertainties on the values of the CO matrix elements. The dashed line is the CS model prediction [3]. The two continuous lines are the predictions of a CS model which uses the k_t factorisation [4], the two lines refer to two different un-integrated gluon distributions [5]. All the theoretical predictions are in agreement with the data for λ vs. z , while only the CS model seems to follow the data for λ vs. p_T . In Fig.1 (c), the ν parameter is shown vs. p_T (in the phase space region $0.4 < z < 0.9$ and $50 < W < 180 \text{ GeV}$) and in Fig.1 (d) the ν parameter is shown vs. z (in the phase space region $p_T > 1 \text{ GeV}$ and $50 < W < 180 \text{ GeV}$). The theoretical curves in the plots have the same meaning as explained for λ . In the ν vs. p_T plot, the CS+CO and the k_t models are in agreement with the data, while the CS model is systematically above the data. In the ν vs. z plot, only the CS+CO model is in rough agreement with the data, while the CS model is always above the data and the k_t factorisation is always below the data.

4 Conclusions

The J/ψ helicity distributions in inelastic photoproduction have been measured by the ZEUS collaboration and compared to LO QCD predictions both in the CS, CS+CO and k_t factorisation frameworks. None of the present models gives a fully satisfactory description of the data. Higher-order corrections are not expected to change the theoretical picture very significantly [6]. However, a better theoretical understanding is necessary to interpret the data within the framework of QCD.

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^cW is the photon-proton centre of mass energy.

Figure 1: Distribution of the helicity parameter λ as a function of p_T , Fig. (a), and z , Fig. (b). Distribution of the helicity parameter ν as a function of p_T , Fig. (c), and z , Fig. (d). The inner error bars correspond to the statistical uncertainties, the outer error bars to the statistical and systematic uncertainties summed up in quadrature. The theoretical curves are described in the text.