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Inelastic J/ψ production at HERA

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Abstract. This article reviews the recent experimental results obtained by the H1 and ZEUS Collaborations at HERA in the study of the inelastic J/ψ production. Emphasis will be placed on the comparison between data and theoretical developments in the quarkonium production field.

PACS. 12.38.Qk Experimental tests – 12.38.Bx Perturbative calculations

1 Introduction

The production of heavy quarkonium in high energy *ep* collisions provides an important tool to study the interplay between perturbative and non-perturbative dynamics. In the following, firstly we give a brief summary of the theory, then we compare results obtained in photoproduction and in electroproduction regimes with theoretical models, followed by conclusions.

2 The theoretical framework

A recent and exhaustive review of the theoretical situation regarding quarkonium production at high-energy colliders (both at HERA, Tevatron and at LHC) can be found in [1]. In *ep* collisions charmonium can be produced inelastically both through direct photon and resolved photon processes. 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. The charmonium 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 parameterized 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). If one introduces the inelasticity variable $z = P \cdot p_{\psi} / P \cdot q$, the direct photon CS process will dominate at medium z values, while resolved photon CS is present only at low z values. CO contributions will give sizable contributions in the high z (direct photon CO) and in the low z region (resolved photon CO) of the $d\sigma/dz$ distribution.

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3 Inelastic J/ψ photoproduction

In Fig. 1 we show the differential photoproduction[1] cross section $d\sigma/dz$ from the ZEUS Collaboration [2] (black points) for a photon-proton center of mass energy (W) between 50 and 180 GeV, and for transverse momentum (p_t) of the J/ψ greater than 1 GeV. In the same plot, the empty points represent H1 data [3] scaled down to the ZEUS phase space, while the empty squares are H1 data [3] collected in a high W and low z region. In Fig. 2 is shown the differential photoproduction cross section $d\sigma/dp_t^2$ from ZEUS Collaboration [2] (black points) for $0.4 < z < 0.9$ and $50 < W < 180$ GeV (empty points are H1 data [3] scaled down to the ZEUS phase space). In both figures the direct CS next-to-leading order (NLO) calculation [4], represented by the *shaded regions*, gives the right normalization and shape. The theoretical uncertainty is large and it is driven by the dependence on the charm mass ($1.3 < m_c < 1.6$ GeV) and the α_s ($0.117 < \alpha_s < 0.121$). In Fig. 2 the dotted line represents direct CS leading order (LO) calculation [4], for $p_t^2 \sim 1$ GeV^2 the prediction underestimates the data by a factor of about two, although this is within the range of theoretical uncertainties. For higher p_t values, the calculation falls increasingly below the data: in conclusion there is an absolute necessity of NLO corrections.

[1] When the virtuality (Q^2) of the exchanged intermediate photon is low ($Q^2 \leq 1$ GeV^2), we speak of photoproduction regime, in this case the scattered electron escapes along the beampipe and it is not seen in the main detector.

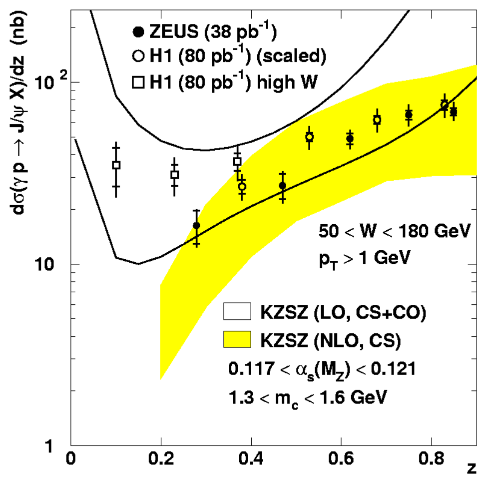

Fig. 1. Differential cross section $d\sigma/dz$ for $50 < W < 180$ GeV and $p_t > 1$ GeV: black points from ZEUS Collaboration [2], empty points from H1 Collaboration [3]. The empty squares come from H1 Collaboration [3]. The *shaded band* shows the prediction of direct CS NLO calculation [4], the *solid lines* the prediction of a LO calculation [1] including both direct and resolved photon processes with CS and CO terms

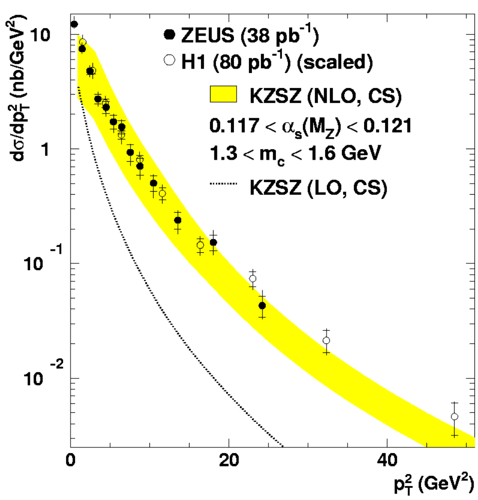

Fig. 2. Differential cross section $d\sigma/dp_t^2$ for $50 < W < 180$ GeV and $0.4 < z < 0.9$: black points from ZEUS Collaboration [2], empty points from H1 Collaboration [3]. The *shaded band* shows the prediction of direct CS NLO calculation [4]. The *dotted line* represents the CS LO prediction [4]

In Fig. 1 the region between the two solid lines represents a LO calculation [1] summing direct plus resolved photon processes with CS and CO terms (with octet matrix elements fixed using CDF J/ψ data). The calculation gives a reasonable description of the data, having in mind the large theoretical uncertainties affecting the LO calculations. The increase at low z is due to the CS and CO resolved photon contributions, this is supported by the H1 data at high W value. The CO is also expected to give sizable contribution at high z values, but this is not supported by the data. It has been demonstrated [5] that at high z a LO calculation shows divergent behaviour due to soft gluon emission, it is necessary to take into account the kinematic effect of the soft gluon emission in the fragmentation process through a resummation procedure, and a higher p_t cut is desirable to improve the theoretical stability. The last two requirements (resummation and higher p_t cut) are addressed in Fig. 3, where H1 [3] data with $p_t > 3$ GeV are compared with a LO calculation [6] in which the resummation was made. With a value of the resummation parameter Λ between 300 MeV and 500 MeV a better description of the high z spectrum is obtained.

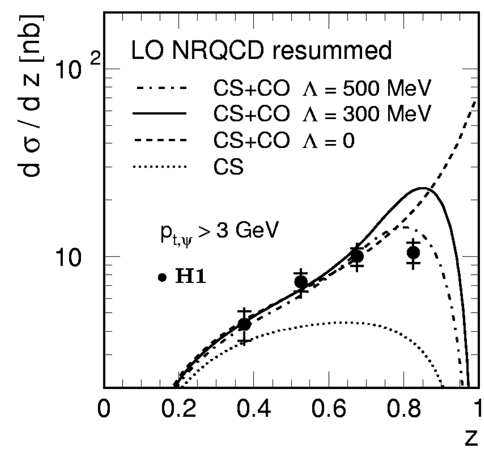

Fig. 3. Differential cross section $d\sigma/dz$ for $60 < W < 240$ GeV and $p_t > 3$ GeV (points) from H1 Collaboration [3] in comparison with NRQCD calculations [6] including CO and CS contributions after resumming soft contributions at high z. The *curves* correspond to three values of the parameter $\Lambda = 0$ (no resummation), 300 MeV and 500 MeV (*dashed, full* and *dash-dotted*). The *dotted line* is the CS contribution alone

4 Helicity distributions

Helicity distributions, which are sensitive to the underlying production mechanism (singlet vs. octet), contain less dependence on parameters such as: $m_c, \alpha_s, \mu_R, \mu_F$ and parton distributions due to the fact that they are normalized distributions. H1 and ZEUS Collaborations have measured the helicity distribution parameterizing the data in the following manner: $d\sigma/\sigma d\cos\theta^* \propto 1 + \lambda\cos^2\theta^*$, $d\sigma/\sigma d\phi^* \propto 1 + \lambda/3 + (\nu/3) \cdot \cos 2\phi^*$. The quantisation axis is chosen to be the opposite of the incoming proton direction in the J/ψ rest frame, θ^* is the opening angle between the quantisation axis and the μ^+ direction of flight in the J/ψ rest frame, ϕ^* is the angle of the μ^+ with respect to the plane determined by the incoming photon and proton. λ and ν are the helicity parameters. This frame is known as the "target frame". Figures 4 and 5 show the dependence of λ on p_t for $0.4 < z < 0.9$ and of ν on z for $p_t > 1$ GeV, respectively. The data, collected in the photoproduction regime, come from ZEUS [7] and H1 [3] Collaborations. The values $\lambda = -1$ and $\lambda = +1$ correspond to fully longitudinal and transverse

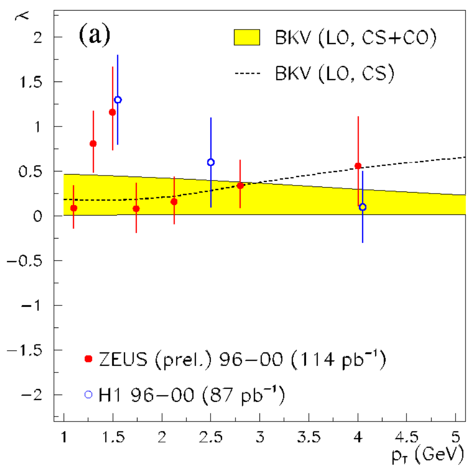

Fig. 4. J/ψ helicity parameter λ as function of p_t for $0.4 < z < 0.9$: black points from ZEUS Collaboration [7], empty points from H1 Collaboration [3]. The prediction of a LO CS+CO calculation [8] is shown as the *shaded band*, the prediction of a LO CS calculation [8] is shown as the *dashed line*

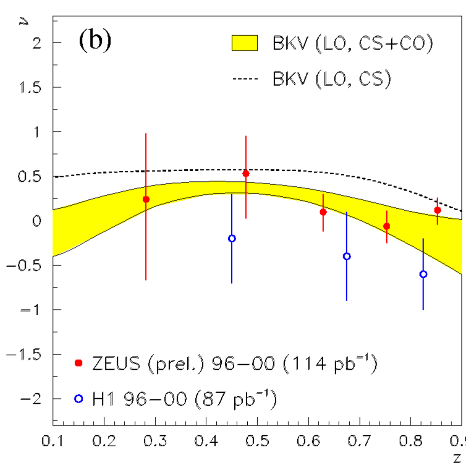

Fig. 5. J/ψ helicity parameter ν as function of z: black points from ZEUS Collaboration [7], empty points from H1 Collaboration [3]. The prediction of a LO CS+CO calculation [8] is shown as the *shaded band*, the prediction of a LO CS calculation [8] is shown as the *dashed line*

polarisation, respectively. The shaded band in the two figures is the prediction of a LO CS+CO calculation [8], the spread in the prediction is due to the theoretical uncertainties on the values of the CO matrix elements. In the currently accessible p_t range, the CS+CO predictions are similar to those of the CS only, although the prediction from the CS model rises with p_t, while the CS+CO prediction decreases slightly. The ν parameter seems to be a more promising variable in order to establish the relative weight of CS and CO contributions. Higher statistics is required for any firm conclusion, which will be provided with the HERA-II upgrade program.

5 Inelastic J/ψ electroproduction

Analyzing leptoproduction at finite Q^2 has experimental and theoretical advantages compared with photoproduction. At high Q^2 theoretical uncertainties in the models decrease and resolved photon processes are expected to be negligible. Furthermore background from diffractive production of charmonia is expected to decrease faster with Q^2 than the inelastic process. The distinct signature of the scattered lepton makes the process easier to detect. Both ZEUS [9] and H1 [10] Collaborations have done measurements in the electroproduction regime. The experimental results were compared with existing LO (CS and CS+CO) theoretical calculations [11,12]. The same features already found in the photoproduction regime are evident also in the high Q^2 regime: the CS+CO calculation grows rapidly in the high z region (lack of soft gluon resummation), while the data don't show this trend, CS calculation alone doesn't describes the $\mathrm{d}\sigma/\mathrm{d}p_t^2$ differential cross-section, it is too steep and this is due to the lack of higher order terms. The theoretical calculations fail to predict the absolute normalization of the various differential cross sections: CS alone is too low , CS+CO is too high.

6 Conclusions

Using data from HERA-I running period, H1 and ZEUS Collaborations have produced accurate inelastic J/ψ cross section measurements both in photoproduction and in electroproduction regimes. In order to understand the relevance of CO contributions in the production of J/ψ in *ep* collision it is mandatory to have NLO calculations in NRQCD both for electro- and photoproduction regime.

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