J/ψ Photoproduction at HERA

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After a short introduction to the theory of Non-Relativistic QCD, we review the production mechanisms at work in J/ψ photoproduction at HERA. Beside the tree-level contributions, we focus on the colour-singlet transition and compare the predicted distributions of events at next-to-leading-order in α_s to the ZEUS data. We also present the recent computation of the radiative corrections to the polarisation parameters of the J/ψ. Based on these results, we argue that the colour-singlet transition alone does not capture all the features revealed by the data collected at HERA.

1 Introduction

Quarkonium bound states offer a unique opportunity to test our understanding of the Quantum Chromodynamics (QCD). Their production in high-energy collisions involves different energy scales. The dynamics of the bound state is characterized by low-enegy effects that cannot be handled perturbatively. The creation of the heavy quarks, owing to their large mass, also implies an energy scale at which the dynamics of strong interactions can be treated as a perturbation, by virtue of the asymptotic freedom of QCD. An effective field theory called Non-Relativistic QCD (NRQCD) [1] is commonly used to disentangle high- from low-energy scales. Soft effects are incoded into long-distance matrix elements that are universal, leaving a process-dependent part that can be computed within perturbation QCD. One consequence of this procedure is the possibility for the heavy-quark pair to be created in a colour-octet state, the colour being neutralised through the low-energy interactions between the heavy-quark pair and the other partons in the event.

Despite its theoretical appeal, not all of the predictions of the NRQCD factorisation approach have been firmly established. Among the open questions stands the universality of the colour-octet long-distance matrix elements: colour-octet transitions in the production of S-wave quarkonium states seem to play a dominant role in hadronic collisions, but they look marginal in photoproduction at HERA. A deeper phenomenological inverstigation seems needed to improve our understanding of the mechanisms at work in quarkonium production.

In this proceeding, we review the situation for J/ψ photoproduction at HERA. In Section 2, we recall the tree-level mechanisms at work for J/ψ photoproduction. In Section 3, we compare the ZEUS data to the next-to-leading order predictions for differential cross sections and polarisation parameters relative to the colour-singlet transition. We give our conclusion in 4.

2 Tree-level contributions

Already at tree level, J/ψ production from the photon-proton interaction can proceed through different mechanisms. These mechanisms contribute in different phase-space regions, as we review here. We present the distribution of events with respect to z, the

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fraction of the photon energy carried by the J/ψ in the proton rest frame. We set $m_c = 1.5$ GeV, $\mu_r = \mu_f = 2m_c$ and $\langle \mathcal{O}_{J/\psi}(^3S_1[1]) \rangle = 1.16$ GeV^3. For the octet long-distance matrix elements, we use the values extracted at the Tevatron [2]:

$$\langle O_8(^3S_1)\rangle_{J/\psi} = 0.39\,10^{-2}\ \mathrm{GeV}^3, \quad \langle O_8(^1S_0)\rangle_{J/\psi} + k\frac{\langle O_8(^3P_0)\rangle_{J/\psi}}{m_c^2} = 6.6\,10^{-2}\ \mathrm{GeV}^3$$

with $k = 3.4$.

In the *direct* mechanisms, the photon interacts directly with a parton originating from the proton over distances of order $\frac{1}{m_c}$ or less. At leading order in v —the relative velocity in the J/ψ— the charm-quark pair has to reach a colour-singlet state over short distances, which requires two gluons to connect the charm quark line, in addiction to the photon. At order $\alpha\alpha_s^2$, there are six Feynman diagrams, related by the permutation of the gauge bosons. This born-level contribution to the colour-singlet transition is finite over the whole J/ψ phase-space, and leads to a rather flat distribution in energy (see Fig. 1, (a)). At relative-order v^4, J/ψ production can proceed through an intermediate state $^1S_0^{[8]}$ or $^3P_J^{[8]}$. Each of these states can be reached by attaching a gluon and a photon to the charm-quark line. This leads to an order-$\alpha\alpha_s$ contribution to the production of a J/ψ at zero transverse momentum. Away from $P_T = 0$, the production involves the emission of a gluon, which balances the transverse momentum of the J/ψ. Since this is a higher-order contribution, the associated tree-level computation develops an infrared singularity when the transverse momentum of the final gluon goes to zero. Experimentally, the low-P_T region is cut off in order to get rid of the diffractive contributions. If we apply the same cut in the prediction, then the phase-space integration leads to a finite contribution. The z distribution for $P_T > 1$ GeV is displayed in Fig. 1, (b). The peak at $z = 1$ clearly signals that the perturbation expansion breaks down and that resummation of soft gluon emission is required [3].

So far, we have only considered the *direct* processes, in which the photon directly connects to a parton with a large virtuality. Alternatively, the photon can fragment into a pair of on-shell collinear light quarks, one of them interacting with the proton. The splitting $\gamma(p) \to q(xp)$ cannot be described perturbatively and requires the convolution with a non-pertubative distribution $f_{q/\gamma}(x, Q)$ [4]. As the collinear quarks originating from the photon have a certain probability to hadronize into a vector-like light hadron, which is a source of gluons, one also introduces the distribution $f_{g/\gamma}(x, Q)$ which corresponds to the splitting $\gamma(p) \to g(xp)$. These mechanisms are classified as *resolved-photon* contributions, and lead to other processes of J/ψ production. At leading order in α_s, colour-singlet resolved production is initiated by two gluons. For colour-octet production, the resolved component opens several new contributions, initiated by quarks or gluons. One important

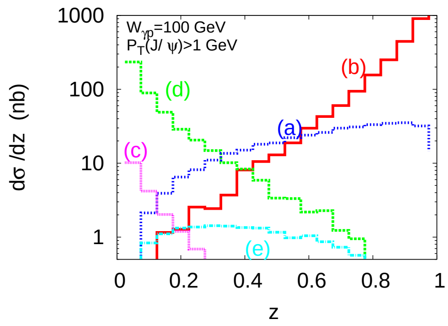

Figure 1: Tree-level contributions to the cross section differential in z: (a) colour-singlet direct, (b) colour-octet direct, (c) colour-singlet resolved, (d) colour-octet resolved, (e) direct colour-singlet associated production

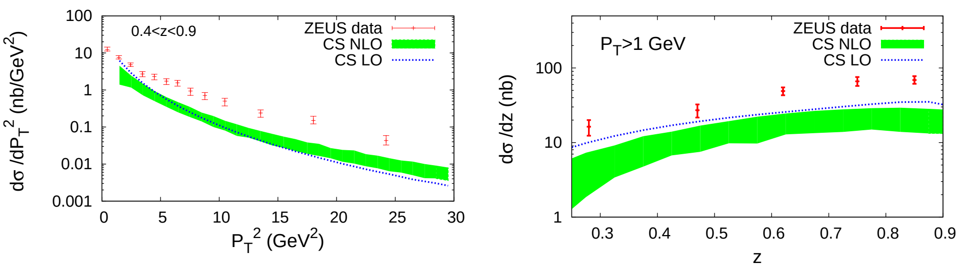

Figure 2: Differential cross sections with respect to P_T^2 (a) and to z (b), compared with the ZEUS data [5].

new channel is colour-octet gluon fragmentation, $g \to c\bar{c}\left({}^3S_1^{[8]}\right)$.

Resolved contributions are relevant only in the low z region, as the fragmentation of a photon into an energetic parton is very rare. As can be seen in Fig. 1, the resolved colour-singlet contribution is negligible for $z \gtrsim 0.2$. The resolved colour-octet component gives a more substantial contribution, but is nevertheless significant only for $z \lesssim 0.4$.

Inelastic contributions to J/ψ production also include the feed-down from excited charmonium states, which we do not take into account here. Feed-down from the $\psi(2S)$ is seen to lead to a 15% increase in the J/ψ cross section [5], whereas contributions from the χ_c states are expected to be smaller ($\approx 1\%$).

3 Colour-singlet observables at Next-to-Leading Order in α_s

In this Section, we compare the measurement published by the ZEUS collaboration [5, 6] to the colour-singlet distributions at order $\alpha\alpha_s^3$. The unpolarised cross section $\sigma(\gamma p \to J/\psi + X)$ in the colour-singlet model was computed in [7] at NLO accuracy in α_S. The computation of the radiative correction to the polarisation parameters has been done more recently [8, 9].

Here we present the analysis in Ref. [8], in which theoretical uncertainties are estimated by varying the scales in the range $2m_c < \mu_{r,f} < 8m_c$, $0.5 < \frac{\mu_r}{\mu_f} < 2$, and the charm quark mass in the range $1.4 - 1.6$ GeV. The resulting distributions in P_T and z are displayed in Fig. 2.

For comparison, we also plot the colour-singlet prediction at leading order in α_S, for which we use the CTEQ6L1 pdf set. As can be seen from Figure 2, the α_S corrections increase the differential cross section in the high P_T region, where the yield is dominated by the new channels that open up at order α_S^3. Nevertheless, the colour-singlet yield at NLO clearly undershoots the ZEUS data. The plots in Figure 2 differ from the comparison presented in [5], where rather extreme values for the renormalization scale were used that have the effect of artificially increasing the normalization.

We now turn to the polarization. Experimentally, the polarization of the J/ψ's can be determined by analyzing the angular distribution of the leptons originating from the decay of the J/ψ. It is convenient to decompose this angular distribution in terms of the polar and azimuthal angles θ and ϕ in the J/ψ rest frame:

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

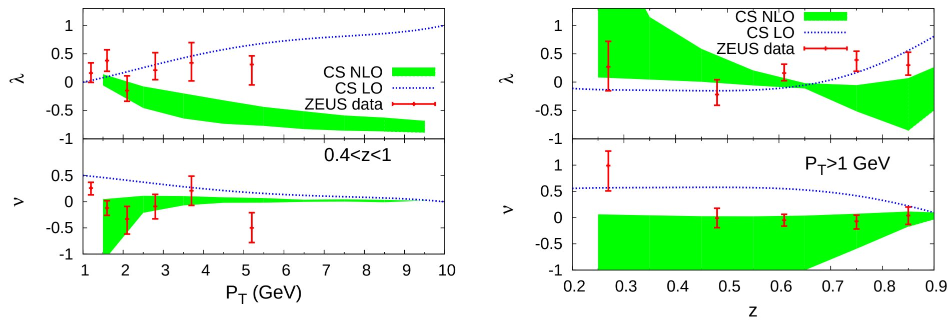

Figure 3: Polarization parameters for colour-singlet production at leading order and next-to-leading order in α_S, compared with the ZEUS measurement [6].

where y stands for a certain (set of) variable(s) (either P_T or z in the following). If the polar axis coincides with the spin quantization axis, the parameters λ, μ, ν can be related to the spin density matrix elements. The spin information that we extract in this way depends on the choice of the quantization axis. Here, we decide to work in the target frame ($\hat{\boldsymbol{z}} = -\frac{\boldsymbol{p}_{\rm p}}{|\boldsymbol{p}_{\rm p}|}$) as this frame has been chosen in the recent analysis performed by the ZEUS collaboration.

The NLO predictions of the polarization parameters associated with colour-singlet production are displayed in Fig. 3, together with the LO predictions and the ZEUS measurements [6]. The band comes from the uncertainties associated with the choice of the scales —varied between $2m_c$ and $8m_c$— which appeared to be much larger then the mass uncertainty. For some specific values of the scales (namely $\mu_r = 2m_c$), the λ and ν parameters appear to be unphysical in some bins. This is due to the fact that, under certain conditions for the scales, our calculation leads to a negative value for the diagonal components of the spin density matrix at $P_T \approx 1$ GeV, and hence cannot be trusted anymore in this region.

QCD corrections to colour-singlet production have a strong impact on the polarization prediction. The most spectacular effect comes from the behavior of the λ parameter at large transverse momentum, for which the prediction is rather stable under the variation of the scales. At leading order in α_S, the colour-singlet transition gives a transverse polarization for the J/ψ at large P_T. Including QCD corrections, we see that the λ parameter decreases rapidly and has a large negative value above $P_T = 4 - 5$ GeV. This situation is similar to what happens in hadro-production, where the J/ψ produced via a colour-singlet transition is longitudinal at large transverse momentum. Such a correction for the λ parameter at moderate and high P_T, as well as the decrease at $z \approx 0.8$, is not supported by the data from the ZEUS collaboration, suggesting the presence of other mechanisms for J/ψ production. In the low z region, the scale uncertainty is too large to draw any conclusion. QCD corrections to colour-singlet production also affect the value of the ν parameter, which goes closer to the experimental data in comparison with the prediction at leading order.

4 Conclusion

For several years, it has been believed that the colour-singlet contribution alone explains measurements of J/ψ photoproduction cross sections. However, as we have shown in the previous section, even when we take into account the order-α_S corrections, colour-singlet production alone does not describe all features of the data collected at HERA. With a natural choice for the renormalization scale, the predicted rate is smaller than the data, even though the shapes of the differential distributions are well described. Moreover, the recent measurement of the J/ψ polarization by the ZEUS collaboration as a function of the P_T shows a very different trend than the theoretical predictions.

The current discrepancies could possibly be solved by invoking colour-octet transitions, i.e. contributions from the intermediate states ${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$. Unfortunately, any phenomenological analysis of the impact of these contributions on differential cross sections and polarization observables is limited by the omission of higher-order corrections that are currently unknown. A complete α_S^3 computation, particularly for the prediction of the polarization of the J/ψ produced via a $P-$wave colour-octet state, would be welcome in order to shed further light on the mechanisms at work in photo-production.

Acknowledgments

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