INCLUSIVE J/ψ PHOTOPRODUCTION AT HERA

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ABSTRACT

I discuss the impact of color-octet contributions to inclusive J/ψ photoproduction at HERA. Emphasis is put on resolved photon processes and on J/ψ polarization, which will be experimentally accessible at HERA in the near future. Both analyses provide a powerful test of the NRQCD factorization approach to charmonium production.

1. Introduction

The production of heavy quarkonium states in high-energy collisions provides an important tool to study the interplay between perturbative and non-perturbative QCD dynamics. While the creation of heavy quarks in a hard scattering process can be calculated in perturbative QCD, the subsequent transition to a physical bound state introduces non-perturbative aspects. A rigorous framework for treating quarkonium production and decays has been developed only recently. The factorization approach is based on the use of non-relativistic QCD (NRQCD) to separate the short-distance parts from the long-distance matrix elements and explicitly takes into account the complete structure of the quarkonium Fock space. According to this formalism, the inclusive cross section for the production of a quarkonium state $H$ can be expressed as a sum of terms, each of which factors into a short-distance coefficient and a long-distance matrix element:

$$d\sigma(H + X) = \sum_n d\sigma(Q\bar{Q}[n] + X) \langle O^n [n] \rangle$$

Here, $d\sigma$ denotes the short-distance cross section for producing an on-shell $Q\bar{Q}$-pair in a colour, spin and angular-momentum state labelled by $n$. The universal NRQCD matrix elements $\langle O^n [n] \rangle$ give the probability for a $Q\bar{Q}$-pair in the state $n$ to form the quarkonium state $H$. The relative importance of the various terms in (1) can be

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estimated by using NRQCD velocity scaling rules. For $v \rightarrow 0$ ($v$ being the average velocity of the heavy quark in the quarkonium rest frame) each of the NRQCD matrix elements scales with a definite power of $v$ and the general expression (1) can be organized into an expansion in powers of the heavy quark velocity. The general factorization formula (1) is believed to hold also for quarkonium production in hadron-hadron or photon-hadron collisions. In the case of inclusive open heavy flavour production it has been shown that the hadronic cross section factorizes into a partonic hard scattering cross section multiplied by light quark and gluon parton densities, with higher-twist corrections being suppressed by powers $\Lambda_{\text{QCD}}/m_Q$. The argument involves averaging over a sufficiently large range of the heavy quark transverse momentum $p_T$ and uses the fact that the main contribution to the total inclusive cross section comes from $p_T \sim m_Q \gg \Lambda_{\text{QCD}}$. Unfortunately, the situation is more involved for quarkonia production in hadronic collisions, since the region of small transverse $Q_Q$ momentum significantly contributes to the total cross section. At small transverse momentum however, the intermediate colour-singlet or colour-octet $Q\bar{Q}$ pair moves parallel with a remnant jet and might interact before the physical bound state has been formed. Only in the heavy quark limit, where all scales involved in the bound state physics are much larger than $\Lambda_{\text{QCD}}$, higher-twist terms are necessarily strongly suppressed. For charmonium production in hadronic collisions, it seems however reasonable to restrict the analysis to the region $p_T \gg \Lambda_{\text{QCD}}$, where the general factorization formula (1) should safely be applicable. Excluding the small $p_T$ region is also necessary to guarantee perturbative stability in higher-order QCD calculations of $J/\psi$ photoproduction.

The NRQCD formalism implies that colour-octet processes, in which the heavy-quark antiquark pair is produced at short distances in a colour-octet state and subsequently evolves nonperturbatively into a physical quarkonium, must contribute to the cross section. As discussed extensively in the literature, colour-octet contributions appear as the most plausible explanation of the large direct $\psi$ production cross section observed at the Tevatron. The NRQCD approach is certainly the correct theory for quarkonium production in the heavy quark limit. It is however not clear whether the charm quark mass is sufficiently large to allow for a reliable expansion in the heavy quark velocity. In order to establish the phenomenological significance of the colour-octet mechanism and the universality of the NRQCD matrix elements for charmonium production it is thus necessary to identify colour-octet matrix elements in different production processes. The analysis of $J/\psi$ photoproduction at HERA appears to be a very powerful tool to constrain the colour-octet matrix elements and to test the picture of quarkonium production as developed in the context of the NRQCD factorization approach.

The production of $J/\psi$ particles in high energy $ep$ collisions at HERA is dominated by photoproduction events where the electron is scattered by a small angle $a$ Higher-twist corrections to colour-singlet $J/\psi$ photoproduction have been analysed recently.
producing photons of almost zero virtuality. The measurements at HERA provide information on the dynamics of $J/\psi$ photoproduction in a wide kinematical region, $30 \text{ GeV} \lesssim \sqrt{s_{\gamma p}} \lesssim 200 \text{ GeV}$, corresponding to initial photon energies in a fixed-target experiment of $450 \text{ GeV} \lesssim E_\gamma \lesssim 20,000 \text{ GeV}$. The production of $J/\psi$ particles in photon-proton collisions proceeds predominantly through photon-gluon fusion, where the photon interacts directly with the gluon from the proton. Besides the direct photoproduction channel, $J/\psi$ production at HERA can also take place via resolved photon contributions where the photon behaves as a source of partons which interact with the partons in the proton. Resolved processes are expected to contribute significantly to the lower endpoint of the $J/\psi$ energy spectrum and might be probed at HERA for the first time in the near future.$^b$

2. Direct Photon Contributions

For $J/\psi$ production and at leading order in the velocity expansion, the general factorization formula \cite{factorization} reduces to the standard expression of the colour-singlet model\cite{singlet}. The short-distance cross section for $J/\psi$ photoproduction through direct photons is given by the subprocess

$$\gamma + g \rightarrow c\bar{c}[^3S_1, \underline{1}] + g$$ (2)

with $c\bar{c}$ in a colour-singlet state (denoted by $\underline{1}$), with zero relative velocity, and spin/angular-momentum quantum numbers $^{2S+1}L_J = ^3S_1$. Relativistic corrections to the colour-singlet channel due to the motion of the charm quarks in the $J/\psi$ bound state enhance the small-$p_T$ region, but can be neglected for $p_T \gtrsim 1 \text{ GeV}$\cite{relativistic}. The calculation of the higher-order perturbative QCD corrections to the short-distance cross section \cite{hordering} has been performed recently\cite{hordering}. Inclusion of the NLO corrections reduces the scale dependence of the theoretical prediction and increases the cross section significantly, depending in detail on the $\gamma p$ energy and the choice of parameters\cite{NLO}. Details of the calculation and a comprehensive analysis of total cross sections and differential distributions for the energy range of the fixed-target experiments and for $J/\psi$ photoproduction at HERA can be found elsewhere\cite{HERA-PDG}.

The leading colour-octet configurations which contribute to $J/\psi$ photoproduction at $p_T \neq 0$ are produced through the subprocesses\cite{octet1, octet2}

$$\gamma + g \rightarrow c\bar{c}[^1S_0, ^3S_1, ^3P_{0,1,2}, \underline{8}] + g$$
$$\gamma + q(\bar{q}) \rightarrow c\bar{c}[^1S_0, ^3S_1, ^3P_{0,1,2}, \underline{8}] + q(\bar{q})$$ (3)

The transition of the colour-octet $c\bar{c}[^{2S+1}L_J, \underline{8}]$ pairs into a physical $J/\psi$ state through the emission of non-perturbative gluons is described by the long-distance matrix

\footnotesize

$^b$Elastic mechanisms only contribute to the region of small $J/\psi$ transverse momentum and can be suppressed by an appropriate cut in $p_T$\cite{elastic}.
elements $\langle O^{J/\psi \ [2S+1L_J, S]} \rangle$. They have to be obtained from lattice simulations or measured directly in some production process. According to the velocity scaling rules of NRQCD, the colour-octet matrix elements associated with $S$-wave quarkonia should be suppressed by a factor of $v^4 \sim 10^{-2}$ compared to the leading colour-singlet matrix element. However, explicit calculation of the processes (3) shows that the short-distance factors of the $[1^3S_0, S]$ and $[1^3P_0, 2, S]$ channels are strongly enhanced as compared to the colour-singlet term and compensate the $O(10^{-2})$ suppression of the corresponding non-perturbative matrix elements. This short-distance enhancement is due to $t$-channel gluon exchange which contributes to the $[1^3S_0, 3^3P_0, 2, S]$ cross sections, but not to the leading-order colour-singlet channel.

3. Resolved photon contributions

Inclusive $J/\psi$ photoproduction can also take place via resolved photon interactions, where the photon first splits into a flux of light quarks and gluons which then may fuse with a gluon or light quark from the proton to form a $c\bar{c}$ pair. This process has been extensively analyzed in the past in the framework of the colour-singlet model, where the cross section is given by gluon-gluon fusion into a $3^3S_1$ colour-singlet $c\bar{c}$ pair, which subsequently hadronizes into a $J/\psi$:

$$g + g \rightarrow c\bar{c} \ [3^3S_1, 1] + g$$

(4)

The process (4) contributes to the overall cross section only marginally except near the lower endpoint of the $J/\psi$ energy spectrum.

Within the NRQCD factorization approach, however, more resolved-photon channels have to be considered, where $J/\psi$ production proceeds via colour-octet $c\bar{c}$ pairs. The leading colour-octet contributions are:

$$g + g \rightarrow c\bar{c} \ [1^3S_0, 3^3S_1, 3^3P_{0,1,2}, S] + g$$
$$g + q(\bar{q}) \rightarrow c\bar{c} \ [1^3S_0, 3^3S_1, 3^3P_{0,1,2}, S] + q(\bar{q})$$
$$q + \bar{q} \rightarrow c\bar{c} \ [1^3S_0, 3^3S_1, 3^3P_{0,1,2}, S] + g$$

(5)

They are in every respect analogous to the ones which have been argued to strongly increase the $J/\psi$ production cross section in $p\bar{p}$ collisions at the Tevatron. Colour-octet contributions to resolved $J/\psi$ photoproduction thus provide an important direct test of the NRQCD explanation of the Tevatron data.

4. The $J/\psi$ Energy Distribution

The $J/\psi$ energy distribution $d\sigma/dz$ offers unique possibilities to study the relative importance of the different mechanisms that contribute to $J/\psi$ photoproduction. The scaling variable $z$ is defined by $z = p \cdot k_\psi / p \cdot k_\gamma$, $p, k_\psi, k_\gamma$ being the momenta of
the proton and $J/\psi$, $\gamma$ particles, respectively. In the proton rest frame, $z$ is the ratio of $J/\psi$ to $\gamma$ energy, $z = E_\psi / E_\gamma$. Adopting NRQCD matrix elements consistent with those extracted from the fits to prompt $J/\psi$ data at the Tevatron (see Table), one finds significant colour-octet contributions near the upper and lower endpoint of the $J/\psi$ energy spectrum. This is demonstrated in Fig. 1, where I plot the Table 1. Values of the NRQCD matrix elements used in the numerical analysis, with the velocity and mass scaling.

| Matrix Element                      | Value       | Mass Scaling |
|------------------------------------|-------------|--------------|
| $\langle O^{J/\psi}_{3S_1, 1} \rangle$ | $1.16 \text{ GeV}^3$ | $m_c^3 \psi^3$ |
| $\langle O^{J/\psi}_{1S_0, 8} \rangle$ | $10^{-2} \text{ GeV}^3$ | $m_c^3 \psi^7$ |
| $\langle O^{J/\psi}_{3S_1, 8} \rangle$ | $10^{-2} \text{ GeV}^3$ | $m_c^3 \psi^7$ |
| $\langle O^{J/\psi}_{3P_0, 8} \rangle / m_c^2$ | $10^{-2} \text{ GeV}^3$ | $m_c^3 \psi^7$ |

colour-singlet and colour-octet contributions to $d\sigma/dz$ at a typical HERA energy of $\sqrt{s_{\gamma p}} = 100 \text{ GeV}$ in the restricted range $p_\perp \geq 1 \text{ GeV}$ via direct and resolved photon processes. The colour-octet processes are predicted to exceed the colour-singlet ones by more than an order of magnitude for $z \gtrsim 0.6$ and $z \lesssim 0.2$. Resolved contributions are negligible for $z \gtrsim 0.3$, but colour-octet terms are expected to become significant at the lower end of the energy spectrum. The theoretical predictions are compared to experimental results obtained by the H1 and ZEUS collaborations at HERA. From Fig. 1, one can conclude that the large colour-octet enhancement in the region $z \gtrsim 0.6$ is not supported by the experimental data and that the $J/\psi$ energy spectrum is adequately described by the colour-singlet channel. Taking into account the large uncertainty of the cross section normalization due to the choice for the charm quark mass and the QCD coupling, the current experimental data on the $J/\psi$ energy distribution can be accounted for by the colour-singlet channel alone. This can be judged by comparing the experimental data with the shaded band in Fig. 1 which indicates how much the colour-singlet cross section is altered if $m_c$ and $\Lambda^{(4)}$ vary in the range $1.35 \text{ GeV} < m_c < 1.55 \text{ GeV}$ and $200 \text{ MeV} < \Lambda^{(4)} < 300 \text{ MeV}$.

One should be careful to interpret the discrepancy between the theoretical predictions for the colour-octet contributions and the HERA data shown in Fig. 1 as a failure of the factorization approach. As pointed out recently, the NRQCD expansion breaks down close to the phase space boundary $z \to 1$, and no prediction can be made for $z \gtrsim 0.75$ without resumming large corrections in the velocity expansion. Therefore, the shape of $d\sigma/dz$ near the endpoint region cannot be used to access the importance of colour-octet contributions. Nevertheless, the analysis of the

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$^a$Note that a cut in the $J/\psi$ transverse momentum, $p_T \gtrsim 1 \text{ GeV}$, is sufficient to exclude the elastic contributions; no additional cut in $z$ is required.

$^b$Similarly, colour-octet processes enhance the low-$z$ region in $J/\psi$ photoproduction at large $p_T$ via fragmentation mechanisms.

$^c$To study the $\alpha_s$ dependence of the cross section, I use consistently adjusted sets of parton densities.
Fig. 1. Colour-singlet (CS) and colour-octet (CO) contributions to the $J/\psi$ energy distribution $d\sigma/dz$ at the photon-proton centre of mass energy $\sqrt{s_{\gamma p}} = 100$ GeV integrated in the range $p_T \geq 1$ GeV, compared to experimental data $^{18,19}$. Both direct and resolved photon processes are included. Parameters: $m_c = 1.5$ GeV, renormalization/factorization scale $\mu = 2m_c$, GRV parton distribution functions $^20$ with $\Lambda^{(4)} = 200$ MeV. The shaded band reflects the uncertainty in the normalization of the direct colour-singlet contributions due to variation of $m_c$ and $\alpha_s$, as described in the text.

$J/\psi$ energy distribution provides a crucial constraint on the colour-octet matrix elements if one averages over a sufficiently large interval $\Delta z \gg v^2 \sim 0.25$ containing the endpoint $z = 1$, as shown in Fig. 2. Colour-octet mechanisms should contribute significantly to the region $0.6 \lesssim z \leq 1$ and exceed the colour-singlet cross section by more than an order of magnitude. While the overall size of the cross section is subject to large uncertainties due to $m_c$ and $\alpha_s$, the distinctive modification of the $J/\psi$ energy spectrum by colour-octet processes in the low and large $z$ region should clearly be visible in the experimental data. Moreover, the low-$z$ region of the energy spectrum is not expected to be sensitive to higher order terms in the velocity expansion and can thus reliably be predicted within leading-twist NRQCD.

The results at HERA seem to indicate that the values of the colour-octet matrix elements $\langle O^{J/\psi}[S_0,\bar{S}] \rangle$ and $\langle O^{J/\psi}[P_0,\bar{S}] \rangle$ are considerably smaller than suggested by the fits to the CDF data at the Tevatron. This does however not necessarily imply the non-universality of the NRQCD matrix elements for $J/\psi$ production. The determina-
Fig. 2. Same as Fig. 1, averaged over large intervals in $z$.

tion of the $\langle O^{J/\psi}[^1S_0, S]\rangle$ and $\langle O^{J/\psi}[^3P_0, S]\rangle$ matrix elements from the Tevatron data is very sensitive to all effects that modify the shape of the $J/\psi$ transverse momentum distribution at $p_t \lesssim 5$ GeV and might yield much too large values. The theoretical uncertainties include the small-$x$ behaviour of the gluon distribution, the evolution of the strong coupling, next-to-leading order contributions, intrinsic transverse momentum of the partons in the proton, and also systematic effects inherent in NRQCD, such as the inaccurate treatment of the energy conservation in the hadronization of the colour-octet $c\bar{c}$ pairs. With higher statistics data at HERA it will be possible to extract more detailed information on the colour-octet matrix elements, in particular from the analysis of the $J/\psi$ energy distribution.

5. $J/\psi$ Polarization

The NRQCD factorization approach allows for unambiguous predictions of the quarkonium polarization. Transverse polarization of $J/\psi$ and $\psi'$ particles, produced directly at large transverse momentum in $p\bar{p}$ collisions at the Fermilab Tevatron, has in fact emerged as the most prominent test of colour-octet contributions and spin symmetry in charmonium production. Polarization signatures in $J/\psi$ photoproduction
have been analysed in detail in the past within the colour-singlet model. Recently, a comprehensive calculation has been performed in the context of the NRQCD factorization approach, including colour-singlet and colour-octet contributions to both direct as well as resolved photon processes. Results are available for the most general decay angular distribution in any given reference frame. Here, I only consider the polar-angle distribution in the s-channel helicity frame, in which the polarization axis in the $J/\psi$ rest frame is defined as the direction of the $J/\psi$ three-momentum in the photon-proton cms frame. The polar angular distribution in the decay $J/\psi \to l^+ l^-$ is given by

$$\frac{d\Gamma}{d \cos \theta} \propto 1 + \alpha \cos^2 \theta,$$

with $\theta$ the angle between the lepton three-momentum in the $J/\psi$ rest frame and the polarization axis. Fig. 3 displays colour-singlet and colour-octet contributions to the polar asymmetry $\alpha$, defined in (6), as function of the $J/\psi$ energy variable $z$. It is worth pointing out that the asymmetry predictions involve ratios of cross sections and are thus to a large extent insensitive to uncertainties in the charm quark mass, the QCD coupling or parton distribution functions. Therefore, polarization measurements are a
rather clean test of the underlying quarkonium production mechanisms and will allow to access the relative importance of colour-singlet and colour-octet contributions.

6. Conclusions

I have discussed colour-singlet and colour-octet contributions to $J/\psi$ photoproduction at HERA. The high-statistics data to be expected in the near future will allow the analysis of resolved photon processes and $J/\psi$ polarization to further test the phenomenological significance of colour-octet contributions. Various other channels and final states can be accessed in the future at HERA, like photoproduction of $\psi'$, $\Upsilon$ and $\chi_c$ particles, associated $J/\psi + \gamma$ production, fragmentation contributions at large $p_T$, as well as deep inelastic $J/\psi$ production. The future analyses of inclusive quarkonium production at HERA offer unique possibilities to test the NRQCD factorization approach to charmonium production.

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8. References

1. G.T. Bodwin, E. Braaten and G.P. Lepage, Phys. Rev. D51 (1995) 1125
2. W.E. Caswell and G.P. Lepage, Phys. Lett. B167 (1986) 437
3. G.P. Lepage, L. Magnea, C. Nakhleh, U. Magnea and K. Hornbostel, Phys. Rev. D46 (1992) 4052
4. J.C. Collins, D.E. Soper and G. Sterman, Nucl. Phys. B263 (1986) 37
5. J.P. Ma, Nucl. Phys. B498 (1997) 267; see also S.J. Brodsky, W.-K. Tang and P. Hoyer, Phys. Rev. D52 (1995) 6285
6. M. Krämer, J. Zunft, J. Steegborn and P.M. Zerwas, Phys. Lett. B348 (1995) 657
7. M. Krämer, Nucl. Phys. B459 (1996) 3
8. E. Braaten and S. Fleming, Phys. Rev. Lett. 74 (1995) 3327
9. M. Cacciari, M. Greco, M.L. Mangano and A. Petrelli, Phys. Lett. B356 (1995) 560; P. Cho and A.K. Leibovich, Phys. Rev. D53 (1996) 150 and ibid. 53 (1996) 6203; M. Beneke and M. Krämer, Phys. Rev. D55 (1997) 5269
10. F. Abe et al. [CDF Collab.], Phys. Rev. Lett. 69 (1992) 3704; A. Sansoni, [CDF Collab.], FERMILAB-CONF-95/263-E
11. W. Koepf, P.V. Landshoff, E.M. Levin and N.N. Nikolaev, Proc. “Future Physics at HERA”, Eds. A. de Roeck, G. Ingelman and R. Klanner, DESY, Hamburg, 1996 and references therein; M. Diehl, these proceedings
12. E.L. Berger and D. Jones, Phys. Rev. D23 (1981) 1521; R. Baier and R. Rückl, Phys. Lett. 102B (1981) 364
13. W.Y. Keung and I.J. Muzinich, Phys. Rev. D27 (1983) 1518; H. Jung, D. Krücker, C. Greub and D. Wyler, Z. Phys. C60 (1993) 721; H. Khan and P. Hoodbhoy Phys. Lett. B382 (1996) 189
14. M. Cacciari and M. Krämer, Phys. Rev. Lett. 76 (1996) 4128; P. Ko, J. Lee and H.S. Song, Phys. Rev. D54 (1996) 4312
15. H. Jung, G.A. Schuler and J. Terrón, Proc. “Physics at HERA”, Eds. W. Buchmüller and G. Ingelman, DESY, Hamburg, 1992 and Int. J. Mod. Phys. A7 (1992) 7955
16. M. Cacciari and M. Krämer, Proc. “Workshop on Future Physics at HERA”, Eds. G. Ingelman, A. De Roeck and R. Klanner, DESY Hamburg, 1996
17. B.A. Kniehl and G. Kramer, DESY-97-036 [hep-ph/9703280] and DESY-97-110 [hep-ph/9706363]
18. S. Aid et al. [H1 Collab.], Nucl. Phys. B472 (1996) 3
19. M. Derrick et al. [ZEUS Collab.], presented by L. Stanco at the International Workshop on Deep Inelastic Scattering, Rome, April 1996; R. Brugnera, these proceedings
20. M. Glück, E. Reya and A. Vogt, Z. Phys. C67 (1995) 433; A. Vogt, Phys. Lett. B354 (1995) 433
21. M. Beneke, I.Z. Rothstein and M.B. Wise, CERN-TH-97-086 [hep-ph/9705286]
22. M. Beneke and M. Krämer, B. Cano Coloma, M.A. Sanchis Lozano, IFIC-97-29 [hep-ph/9706270]
23. M. Beneke and I.Z. Rothstein, Phys. Lett. B372 (1996) 157 and Phys. Rev. D54 (1996) 2005 [erratum: ibid. D54 (1996) 7082]; E. Braaten and Y.-Q. Chen, Phys. Rev. D54 (1996) 3216; M. Beneke and M. Krämer
24. P. Cho and M.B. Wise, Phys. Lett. B346 (1995) 129
25. R. Baier and R. Rückl, Nucl. Phys. B201 (1982) 1; J.G. Körner, J. Cleymans, M. Kuroda and G.J. Gounaris, Nucl. Phys. B204 (1982) 6 [erratum: ibid. B213 (1983) 546] and Phys. Lett. 114B (1982) 82
26. M. Beneke, M. Krämer and M. Vänttinen, to be published
27. J.P. Ma, Nucl. Phys. B460 (1996) 109
28. T. Mehen, Phys. Rev. D55 (1997) 4338
29. M. Cacciari, M. Greco and M. Krämer, Phys. Rev. D55 (1997) 7126
30. R. Godbole, D.P. Roy and K. Sridhar, Phys. Lett. B373 (1996) 328
31. S. Fleming, MADPH-96-966 [hep-ph/9610372], talk at “Quarkonium Physics Workshop: Experiment Confronts Theory”, Chicago, IL, 13-15 Jun 1996; S. Fleming and T. Mehen, JHU-TIPAC-96022A [hep-ph/9707362]