Photoproduction of Heavy Quarks

MICHAEL KRAEMER†

Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

Abstract

Heavy quarks are copiously produced in two-photon collisions at \(e^+e^-\) colliders. The theoretical predictions including QCD radiative corrections are compared to recent experimental data on \(\gamma\gamma\) production of charm quarks at PETRA, PEP, TRISTAN and LEP. Photoproduction of heavy quarks at HERA is an important tool to measure the gluon distribution in the proton. New theoretical results on heavy quark photoproduction at large transverse momenta are discussed and NLO predictions for inelastic \(J/\psi\) photoproduction in the HERA energy range are given. The sensitivity of the results to the parametrization of the gluon distribution in the small-\(x\) region is demonstrated.

* Talk presented at the Conference "Photon '95", Sheffield, UK, April 1995; to appear in the proceedings.
† E-mail: mkraemer@desy.de
I. Introduction

The study of heavy flavour production is one of the important areas of research at present and future high-energy colliders. Many features of the production mechanism for heavy quarks are calculable in perturbative QCD. The mass of the heavy quark, \( m \gg \Lambda_{\text{QCD}} \), acts as a cutoff and sets the scale for the perturbative calculations. The production cross section factorizes into a partonic hard scattering cross section multiplied by light quark and gluon parton densities [1]. In order for this approach to be valid the mass of the produced quarks must be sufficiently large for two reasons. First, contributions to the cross section are neglected that are suppressed by powers of \( \Lambda_{\text{QCD}}/m \). After neglecting such power suppressed contributions in order to arrive at a factorized form, one expands the hard scattering cross section in powers of the strong coupling constant \( \alpha_s(m) \), evaluated at a scale set approximately by the heavy quark mass. It is thus not guaranteed \textit{a priori} that charm and bottom quark production can reliably be predicted in perturbative QCD. Higher-twist uncertainties of order \( (\Lambda_{\text{QCD}}/m_c)^2 \sim 20 – 30\% \) have to be taken into account. Moreover, the convergence of the perturbative expansion might be poor due to the large value of the strong coupling constant at the charm mass scale, \( \alpha_s(m_c) \sim 0.3 \). The situation is much better for bottom production, although even there the theoretical uncertainties can be large. The main questions therefore are whether perturbative QCD calculations are trustworthy already for charm and bottom quark production and whether the dynamics of these processes can reliably be described without including non-perturbative effects. The simplest process to study the validity of the perturbative approach is heavy quark production in two-photon collisions. The predictions for the dominant direct production channel do not depend on quark and gluon distributions in the photon so that they are free of phenomenological parameters. They depend only on the heavy quark mass and the QCD coupling.

II. Heavy-Quark Production in Two-Photon Collisions

Three mechanisms contribute to the production of heavy quarks in \( \gamma \gamma \) collisions: (i) In the case of direct production, the photons couple directly to the heavy quarks. No spectator particles travel along the \( \gamma \) axes. (ii) If one of the photons first splits into a flux of light quarks and gluons [2], one of the gluons may fuse with the second photon to form the \( Q\bar{Q} \) pair. The remaining light quarks and gluons build up a spectator jet in the split \( \gamma \) direction (single resolved \( \gamma \) contribution). The total \( \gamma \gamma \) cross section of this mechanism depends on the parton density of the photon [3]. Since the number of gluons in the resolved photon grows \( \sim \alpha s^{-1} \), the resolved \( \gamma \) processes are of the same order as the direct process. (iii) If both photons split into quarks and gluons, the \( Q\bar{Q} \) pair is accompanied by two spectator jets (double resolved \( \gamma \) contribution). It turns out \textit{a posteriori} that the double resolved \( \gamma \) contribution is much smaller than the direct and the single resolved \( \gamma \) contributions.

Two-photon production of heavy quarks can be studied at high-energy \( e^+e^- \) colliders where a large number of equivalent photons is generated. Total cross sections and various distributions for charm and bottom quark production \( e^+e^- \rightarrow e^+e^-c/bX \) have been calculated in Refs. including QCD radiative corrections for the leading subprocesses. The main results of that analysis can be summarized as follows: At low energies in the PETRA/PEP/TRISTAN range, the direct production mechanism by far dominates the total cross section. At LEP2 \( \sim 180 \) GeV, the direct contribution and the 1-resolved \( \gamma \) contribution are of equal size. While the cross sections for charmed particle production are large, giving a total of \( \sim 350,000 \) events for an integrated luminosity of

\[1\] Heavy quark production in deep-inelastic \( e\gamma \) scattering has been discussed by E. Laenen at this conference [4].
at $L = 500 \text{ pb}^{-1}$ at LEP2, $b$ quark production is suppressed by more than two orders of magnitude. The QCD corrections are important, increasing the cross sections by $\sim 30\%$. At the $e^+ e^-$-energies reached up to now the theoretical expectations do not depend much on the parametrization for the quark and gluon densities of the photon. At higher energies the resolved processes are predicted to overtake the direct contribution. A measurement of the gluon content of the photon, which is currently poorly known, might thus be feasible at LEP2.

In Fig. 1 the leading-order and next-to-leading-order calculations for two-photon production of $D^*$ mesons are compared with experimental data from recent measurements [7]. The predictions of the cross sections appear to be theoretically firm. A variation of the charm quark mass $m$ and the renormalization/factorization scale $\mu$ in the range $1.3 \text{ GeV} < \mu < 2m_c$ and $1.3 \text{ GeV} < m_c < 1.8 \text{ GeV}$ leads to a total theoretical uncertainty of $\pm 30\%$ at LEP energies. Even though the statistical and systematic errors are large, the measured charm cross sections appear to overshoot the values estimated at the Born level in the direct channel consistently. Adding however the resolved contributions and the QCD radiative corrections, the agreement with the recent $D^*$ data from PETRA, PEP, TRISTAN and LEP is quite satisfactory. The TOPAZ collaboration reports an excess of $D^*$ data at high transverse momenta which still has to be understood. The VENUS, TOPAZ and AMY collaborations have measured open charm production by tagging leptons from the semi-leptonic charm quark decays [7]. Their results are consistent with the theoretical expectation but seem to favour a rather low charm quark mass and a strong contribution from the resolved process.

Figure 1: Total cross section for $e^+ e^- \rightarrow e^+ e^- D^{*\pm} X$ as function of the $e^+ e^-$-collider energy. Shown is the NLO prediction for $\mu = m_c = 1.3 \text{ GeV}$ (upper short-dashed curve), $\mu = 2m_c; m_c = 1.8 \text{ GeV}$ (lower short-dashed curve), $\mu = \sqrt{2} m_c; m_c = 1.5 \text{ GeV}$ (solid curve) and the prediction for the direct process in leading-order, $\mu = \sqrt{2} m_c; m_c = 1.5 \text{ GeV}$, (long-dashed curve). The results are compared to the recent experimental data [7]. The TPC/2$\gamma$ and TASSO results have been adjusted according to the latest values for the $D^{*+}$ and $D^0$ branching ratios.
III. Heavy-Quark Production in Photon-Proton Collisions

The production of heavy quarks in photon-proton collisions has been studied extensively in fixed target experiments. Total cross sections, single-inclusive distributions as well as heavy-quark correlations have been calculated to next-to-leading-order accuracy \[8\]. All recent total-cross-section data on photoproduction of charm quarks are in reasonable agreement with the NLO QCD predictions, once the theoretical uncertainties are properly taken into account. Supplementing the NLO predictions with a simple parametrization of the most important non-perturbative effects, such as heavy flavoured hadron formation and a moderate intrinsic transverse momentum of the initial state partons, is sufficient to reproduce the experimental data on single- and double-differential distributions \[9\].

The ep collider HERA will provide us with information on the dynamics of heavy flavour production in a kinematical range very different from that available at fixed target experiments. Among the topics to be studied at HERA are photoproduction of charm and bottom quarks in both direct and resolved-photon processes as well as heavy flavour production in deep-inelastic scattering \[10\]. Bottom production is a particular interesting subject to be studied at HERA since the larger value of the bottom quark mass makes QCD predictions more reliable. First HERA results on the total charm photoproduction cross section have been published recently \[11\] and found to be well described by the NLO QCD predictions. The theoretical calculations for the total cross section are based on the standard factorization formula \[1\] where the heavy quark mass \( m \gg \Lambda_{\text{QCD}} \) is considered as the large scale. In next-to-leading order potentially large terms \( \sim \alpha_s \ln(p_\perp/m) \) arise from collinear emission of gluons by a heavy quark at large transverse momentum or from almost collinear branching of gluons or photons into heavy quark pairs. These terms are not expected to affect the total production rates, but they might spoil the convergence of the perturbation series at \( p_\perp \gg m \). An alternative way of making predictions at large \( p_\perp \) is to treat the heavy quarks as massless partons. The mass singularities of the form \( \ln(p_\perp/m) \) are then absorbed into structure and fragmentation functions in the same way as for the light u,d,s quarks. This approach has been used in Ref. \[12\] to study the production of large \( p_\perp \) hadrons containing bottom quarks in \( p\bar{p} \) collisions. Of course, in the massless scheme the heavy quark is considered to be one of the massless active flavours in the proton and, for the resolved contribution, of the photon structure function. In Ref. \[13\] the differential distributions for charm quark production at HERA have been calculated in the massive and the massless approaches up to NLO accuracy.\[3\] The cross section in the massless scheme is approximately 70 – 100% larger than in the massive scheme. This difference can be attributed to the contribution of the charm quark in the photon (for a more detailed discussion and comparison between massive and massless schemes see Ref. \[13\]). A measurement of heavy quark production at large \( p_\perp \) at HERA will provide information about the heavy flavour content of the proton and in particular the photon. Such measurements will be very instructive since theoretical opinions on that issue are rather divided \[13\].

The measurement of the gluon distribution in the nucleon is one of the important goals of lepton-nucleon scattering experiments. The classical methods exploit the evolution of the nucleon structure functions with the momentum transfer and the size of the longitudinal structure function. At HERA energies, however, the production of heavy quark states becomes an important complementary tool. Besides open charm and bottom production, the formation of \( J/\psi \) bound states in inelastic photoproduction experiments provides an experimentally attractive method since \( J/\psi \) particles are

\[2\] This is in contrast to the case of heavy quark hadroproduction where the experimental distributions are much harder than the theoretical expectations \[1\].

\[3\] A similar study, though in leading-order only, has been presented by M. Drees and R. Godbole at this meeting \[14\].
easy to tag in the leptonic decay modes. Inelastic $J/\psi$ photoproduction through photon-gluon fusion is described in the colour-singlet model through the subprocess $\gamma + g \rightarrow J/\psi + g$. Colour conservation and the Landau-Yang theorem require the emission of a gluon in the final state. The cross section is generally calculated in the static approximation in which the motion of the charm quarks in the bound state is neglected. In this approximation the production amplitude factorizes into the short distance amplitude $\gamma + g \rightarrow c \overline{c} + g$, with $c \overline{c}$ in the colour-singlet state and zero relative velocity of the quarks, and the $c \overline{c}$ wave function $\varphi(0)$ of the $J/\psi$ bound state at the origin which is related to the leptonic width. Relativistic corrections due to the motion of the charm quarks in the $J/\psi$ bound state have been demonstrated to be small in the inelastic region [17]. The calculation of the higher-order perturbative QCD corrections has been performed recently [5,18,19]. Inclusion of the NLO corrections reduces the scale dependence of the theoretical prediction considerably and increases the cross section in the energy range of the fixed target experiments, $E_\gamma \sim 100$ GeV, by more than 50%. A comparison of the next-to-leading order calculation with data from the two fixed-target photoproduction experiments [20] reveals that the $J/\psi$ energy dependence $d\sigma/dz$ ($z$ is the scaled $J/\psi$ energy, $z = E_{J/\psi}/E_\gamma$) is adequately accounted for by the colour-singlet model in the inelastic region $z < 0.9$. Thus the shape of the gluon distribution in the nucleon can be extracted from $J/\psi$ photoproduction data with confidence. Similar to the case of open heavy flavour production, the absolute normalization of the cross section shows a strong dependence on the value of the charm quark mass. In the static approximation the choice $m_c = M_{J/\psi}/2$ is required for a consistent description of the heavy bound state formation. However, a smaller mass value might be appropriate for a reasonable description of the charm quark creation in the hard scattering process. Taking $m_c = 1.4$ GeV and allowing for higher-twist uncertainties of order $(\Lambda/m_c)^k \lesssim 30\%$ for $k \geq 1$, one can conclude that the normalization too appears to be under semi-quantitative control [19].

In Fig.2 the NLO prediction of the cross section is presented for the HERA energy range.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{Total cross section for inelastic $J/\psi$ photoproduction $\gamma + P \rightarrow J/\psi + X$ as a function of the photon-proton center of mass energy in the HERA energy range for different parametrizations of the gluon distribution of the proton [21].}
\end{figure}
the momentum fraction of the partons at HERA energies is small, the cross section is sensitive to the parametrization of the gluon distribution in the small-$x$ region $<\xi> \sim 0.001$. As the absolute normalization of the cross section is rather sensitive to the value of $\alpha_s$ and the charm quark mass, the discrimination between different parametrizations of the gluon density in the proton has to rely on the shape of the cross section (as a function of the photon-proton center of mass energy) rather than the absolute size of the prediction. First results on inelastic $J/\psi$ photoproduction at HERA have been presented at this conference [22]. It seems that the theoretical expectation, Fig. 2, underestimates the absolute normalization of the data. With the present statistics, however, no firm conclusion can be drawn.

The cross sections for the inelastic photoproduction of $\psi'$ particles are expected to be $1/4$ of the corresponding $J/\psi$ cross sections. The production of $Y$ bottomonium bound states is suppressed, compared with $J/\psi$ states, by a factor of about 300 at HERA, a consequence of the smaller bottom electric charge and the phase space reduction by the large $b$ mass. The $P$-wave charmonium states $\chi_{c1}$ and $\chi_{c2}$ can be detected in the radiative decay modes $\chi \to J/\psi + \gamma$ at HERA [23]. The predictions for the HERA energy range provide a crucial test for the underlying picture as developed so far in the perturbative QCD sector.

Acknowledgements

Thanks to Fred Combley, David Miller and their colleagues for organizing an interesting and enjoyable meeting.

References

[1] J.C. Collins, D.E. Soper, G. Sterman, Nucl. Phys. B263 (1986) 37.

[2] T.F. Walsh, P.M. Zerwas, Phys. Lett. 44B (1973) 195; E. Witten, Nucl. Phys. B120 (1977) 189.

[3] M. Drees, K. Grassie, Z. Phys. C28 (1985) 451; M. Glück, E. Reya, A. Vogt, Phys. Rev. D46 (1992) 1973. L.E. Gordon, J.K. Storrow, Z. Phys. C56 (1992) 307 and these proceedings; P. Aur- renche, J.P. Guillet, M. Fontannaz, preprint ENSLAPP-A-435-93-REV (1994); G.A. Schuler, T. Sjöstrand, preprint CERN-TH/95-62 (1995); H. Kan, these proceedings.

[4] E. Laenen, S. Riemersma, preprint CERN-TH/95-103 (1995); E. Laenen, S. Riemersma, J. Smith, W.L. van Neerven, Phys. Rev. D49 (1994) 5753.

[5] M. Krämer, PhD. Thesis, Univ. of Mainz, 1994.

[6] M. Drees, M. Krämer, J. Zunft, P.M. Zerwas, Phys. Lett. 306B (1993) 371.

[7] W. Braunschweig et al. [TASSO], Z. Phys. C47 (1990) 499; M. Alston-Garnjost et al. [TPC/2γ], Phys. Lett. 252B (1990) 499; R. Enomoto et al. [TOPAZ], Phys. Rev. D50 (1994) 1879, Phys. Lett. 328B (1994) 535, M. Iwasaki for the TOPAZ coll., these proceedings; S. Uehara et al. [VENUS], Z. Phys. C63 (1994) 213; T. Aso et al. [AMY], preprint KEK-95-19, T. Nozaki for the AMY coll., these proceedings; D. Buskulic et al. [ALEPH], preprint CERN-PPE-95-40, F. Foster for the ALEPH coll., these proceedings.

[8] P. Nason, S. Dawson, R.K. Ellis, Nucl. Phys. B303 (1988) 607; G. Altarelli, M. Diemoz, G. Martinelli, P. Nason, Nucl. Phys. B308 (1988) 724; W. Beenakker, H. Kuijf, W. van Neerven, J. Smith, Phys. Rev. D40 (1989) 54; R.K. Ellis, P. Nason, Nucl. Phys. B312 (1989) 551;
M.L. Mangano, P. Nason, G. Ridolfi, Nucl. Phys. B373 (1992) 295. J. Smith, W.L. van Neerven, Nucl. Phys. B374 (1992) 36; S. Frixione, M.L. Mangano, P. Nason, G. Ridolfi, Nucl. Phys. B412 (1994) 225.

[9] G. Ridolfi, S. Frixione, M.L. Mangano, P. Nason, Nucl. Phys. B431 (1994) 453; G. Schuler, preprint CERN-TH/95-75 (1995).

[10] E. Laenen, S. Riemersma, J. Smith, W.L. van Neerven, Nucl. Phys. B392 (1993) 162, ibid. 229; B.W. Harris, J. Smith, preprint ITP-SB-94-06 and preprint ITP-SB-95-08 (1995).

[11] M. Derrick et al. [ZEUS], Phys. Lett. 349B (1995) 225.

[12] M. Cacciari, M. Greco, Nucl. Phys. B421 (1994) 530.

[13] B.A. Kniehl, M. Krämer, G. Kramer, M. Spira, DESY preprint DESY-95-098 (1995).

[14] M. Drees and R.M. Godbole, preprint LNF-95/020 (P) (1995).

[15] M. Glück, E. Reya, M. Stratmann, Nucl. Phys. B422 (1994) 37; F.I. Olness, S.T. Riemersma, preprint SMU-HEP/94/21 (1994).

[16] E.L. Berger, D. Jones, Phys. Rev. D23 (1981) 1521; R. Baier, R. Rückl, Phys. Lett. 102B (1981) 364; A.D. Martin, C.-K. Ng, W.J. Stirling, Phys. Lett. 191B (1987) 200.

[17] H. Jung, D. Krücker, C. Greub, D. Wyler, Z. Phys. C60 (1993) 721.

[18] M. Krämer, J. Zunft, J. Steegborn, P.M. Zerwas, Phys. Lett. 348B (1995) 657.

[19] M. Krämer, preprint DESY-95-046.

[20] R. Barate et al. [NA-14], Z. Phys. C33 (1987) 505; B.H. Denby et al. [FTPS], Phys. Rev. Lett. 52 (1984) 795.

[21] M. Glück, E. Reya, A. Vogt, preprint DO-TH 94/24; A.D. Martin, R.G. Roberts, W.J. Stirling, Phys. Lett. 306B (1993) 145 and preprint RAL-95-021.

[22] U. Karshon for the ZEUS coll., these proceedings.

[23] W. Kilian, M. Krämer, P.M. Zerwas, DESY preprint in preparation.