Heavy quark photoproduction at THERA

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Abstract

Measurements of heavy quark production at a possible future $ep$ facility, THERA, would provide valuable information on the structure of the photon. QCD cross-section predictions are made at LO for both charm and beauty production and their sensitivity to current parametrisations of the photon parton densities is investigated.

1 Introduction

Heavy quark production can provide information on the structure of the real photon as well as provide stringent tests of QCD by itself. In this paper the potential of the possible future $ep$ collider, THERA, to give new information on the real photon structure through charm and beauty quark photoproduction is studied. The potential of the collider is also compared with other existing or planned colliders.

Photoproduction processes are dominated by the exchange of quasi-real photons (virtuality of the photon $Q^2 \ll 1\text{GeV}^2$). Their energy distribution can be described by an effective (real) photon energy spectrum, i.e. using the Weizsäcker-Williams approximation. A hard scale is provided by a large transverse momentum or the mass of the produced heavy quark $Q$. In this paper the region $p_T \geq m_Q$ is studied. In LO QCD, two processes contribute to the photoproduction of heavy quarks: the direct process, in which the photon couples directly to a parton in the proton, and the resolved process, in which the photon acts as a source of partons, one of which scatters from a parton in the proton. Heavy quarks can be produced in the final state or they already exist in the initial state as partons in the photon and proton, depending on the scheme used in the calculations.

If not stated otherwise the computations were performed with the THERA electron and proton beams energies of 250 GeV and 920 GeV, respectively. In the first section results are presented on LO QCD calculations of inclusive charm quark production, $ep \rightarrow c/\bar{c} X$, at the THERA collider. In particular the possible information this process can reveal on the structure of the photon is discussed. The second section uses MC expectations to investigate events where at least one heavy quark and two jets are produced. Further requirements on a final state muon from a semi-leptonic decay are also imposed and sensitivity to current parametrisations of the photon investigated.
2 Leading order QCD predictions of charm quark production

LO calculations were performed in two schemes which differ by the number of quark flavours which are considered to be part of the structure of the photon and proton, and can thus take part in the process as partons. The massive scheme, the so-called Fixed Flavour Number Scheme (FFNS), assumes that both the photon and proton consist of gluons and only light (u, d and s) quarks whilst heavy quarks are produced in the final state. The massless Variable Flavour Number Scheme (VFNS), considers heavy quarks as active flavours. Therefore such partonic processes, $Q + g \rightarrow Q + g$ or $Q + \bar{Q} \rightarrow Q + \bar{Q}$, with $Q$ denoting a heavy quark, are also allowed. (Events in which the heavy quark is one of the active partons are also referred to as “flavour-excitation”.) In the FFNS scheme the mass of the produced charm quark is always kept nonzero in the calculations while in the VFNS all flavours are treated as massless.

In the massive (FFNS) calculations the number of active flavours ($N_f$) is taken to be 3. In the massless (VFNS) scheme it varies from 3 to 4 depending on the value of the hard (factorisation and renormalisation) scale, $\mu$. The charm quark is included in the computation provided that $\mu > m_c$ with the mass of the charm quark set to $m_c = 1.5\text{GeV}$. Also the QCD energy scale, $\Lambda_{QCD}$, which appears in the one loop formula for the strong coupling constant $\alpha_s$ is affected by the change of the number of active flavours, so is denoted as $\Lambda_{QCD}^{N_f}$. The scale is taken to be $\Lambda_{QCD}^3 = 232\text{MeV}$ and $\Lambda_{QCD}^4 = 200\text{MeV}$ as in the GRV\footnote{The old GRV('92) parametrisation was used in this analysis. It treats heavy quarks as massless above the heavy quark threshold region ($W \gg 2m_Q$), and moreover latest experimental results\footnote{indicate that its gluon distribution is closest to the data.}} parametrisation of the photon $[1]$. If not stated otherwise $\mu$ is taken to be the transverse mass of the produced charm quark, $m_T = \sqrt{m_c^2 + p_T^2}$, and the differential cross-section, $d^2\sigma/d\eta dp_T^2$, with $p_T = 10\text{GeV}$ is calculated. This means that $\mu \sim p_T$ and therefore $N_f = 4$ in case of the VFNS calculations. The spectrum of the quasi-real photons taking part in the process is described by the Weizsäcker-Williams (EPA) formula,

$$f_{\gamma/e}(y) = \frac{\alpha}{2\pi} \left[ \frac{1 + (1 - y)^2}{y} \ln \frac{Q_{max}^2}{Q_{min}^2} + 2m_c^2 y \left( \frac{1}{Q_{max}^2} - \frac{1}{Q_{min}^2} \right) \right],$$

(1)

where $Q_{max}^2 = 4\text{GeV}^2$, $Q_{min}^2 = m_c^2 y^2/(1 - y)$ and $y$ is the fraction of the electron’s four-momentum carried by the photon ($y = E_\gamma/E_e$). No requirements were placed on $y$. Finally the LO CTEQ5L\footnote{and GRV were used as the parton parametrisations of the proton and photon, respectively.} and GRV\footnote{were used as the parton parametrisations of the proton and photon, respectively.} were used as the parton parametrisations of the proton and photon, respectively.

To show the power of the THERA collider for heavy quark physics it is useful to compare the cross-section for charm production that can be achieved in THERA with cross-sections expected for other existing or planned accelerators. In Fig. a comparison with results from the ep HERA ($E_e = 27.5\text{GeV}$, $E_p = 920\text{GeV}$), LEP ($E_e = 90\text{GeV}$), a Linear Collider (LC) and a Photon Collider (PC) both with $E_e = 250\text{GeV}$ are presented for two options of THERA, ep and $\gamma p$. Real photons in the PC and $\gamma p$ THERA option can be achieved through the Compton backscattering laser photons from the electron beam\footnote{and GRV were used as the parton parametrisations of the proton and photon, respectively.} (the full theoretical spectrum for $0 < y < 0.83$ was used). It can be seen that THERA provides the largest cross-sections over the whole range in $\eta$ and has the potential to probe regions kinematically inaccessible at other colliders.

It has been demonstrated elsewhere\footnote{It treats heavy quarks as massless above the heavy quark threshold region ($W \gg 2m_Q$), and moreover latest experimental results\footnote{indicate that its gluon distribution is closest to the data.}} that there is a large dependence of the cross-section for heavy quark production on the choice of scheme for the case of HERA energies. It is also true for the THERA collider. Direct and resolved contributions to the cross-section for charm
production obtained using the two discussed schemes clearly show this dependency, as displayed in Fig. 3. Note that the resolved and direct cross-sections are similar for the VFNS scheme whereas in the FFNS scheme, the resolved cross-section is small compared to that of the direct contribution. The small difference between the direct cross-sections for the two schemes is due to the mass term in the matrix elements and phase space integral. Figure 3 presents the cross-sections with their dependence on the choice of the $\mu$ varied from $1/2m_T$ to $2m_T$. The dependence on the choice of scheme is most significant for resolved processes, varying by up to several orders of magnitude in the cross-section. In the case of direct processes the variation is relatively small and the subsequent total cross-section prediction variation is therefore dominated by the difference between the two schemes for the resolved process. The variation in the choice of scale leads to small effects in the cross-section in comparison with the scheme dependence as it only influences the value of $\alpha_s$ and the parton densities and not the set of allowed partonic processes.

To test the sensitivity of inclusive charm production to the form of the parton densities in the photon, cross-sections for this process were computed with three different LO parton parametrisations of the photon: GRV [1], GS96 [7] and SaS1D [8]. Sensitivity to the form of the current parametrisations of the photon structure function at the THERA collider is larger than at HERA as shown in Fig. 4a (the results of the VFNS calculation). Note that the SaS1D and GRV parametrisations give similar results. Figure 4b shows the uncertainty resulting from the variation of the hard scale by a factor of two compared to the central value. Here it is demonstrated that the differences between the cross-sections obtained using three parton parametrisations of the photon are significant for GRV (or SaS1D) and GS96 in the region $-2.5 < \eta < 0$, despite this large theoretical uncertainty.
Figure 2: THERA. (a) Direct and (b) resolved contributions to the differential cross-section of $ep \rightarrow c/\bar{c} X$ production calculated for $p_T = 10$ GeV in the VFNS (solid lines) and FFNS (dashed lines) schemes using the CTEQ5L and GRV LO parton parametrisations of the proton and photon, respectively.

Figure 3: THERA. Differential cross-section of $ep \rightarrow c/\bar{c} X$ production calculated for $p_T = 10$ GeV in the VFNS (solid lines) and FFNS (dashed lines) schemes with three different values of the hard scale; $\mu = 1/2, 1$ and $2 \times m_T$, using the CTEQ5L and GRV LO parton parametrisations of the proton and photon, respectively.
The differences between two current parton parametrisations of the photon, GRV and SaS1D, have previously been compared for LC and PC colliders [9]. More specifically, the relative difference $\frac{GRV - SaS1D}{GRV}$ of the cross-section, $d^2\sigma/d\eta dp_T^2(ep \to c/\bar{c} X)$, was calculated in both VFNS and FFNS schemes. Values of $\sim 0.1 - 0.4$ were found with the PC having the larger value. Similar numbers (up to 0.3) to those for the LC and PC could be achieved at THERA in the forward $\eta$ region. The massive FFNS gives the same results for the considered sensitivity as those of the massless VFNS scheme.

Figure 4: Differential cross-section for $ep \to c/\bar{c}X$ for $p_T = 10$ GeV calculated with the CTEQ5L parton parametrisation of the proton and three various LO parton parametrisations of the photon in the massless (VFNS) scheme. A) Lower lines correspond to the HERA collider energies (27.5×920 GeV), while upper to the THERA collider energies. B) Lower and upper lines for each photon parametrisation show respectively the lowest and greatest values of the cross-section calculated with different values of the hard scale $\mu = 1/2, 1, 2 \times m_T$ in the GRV case and $\mu = 1, 2 \times m_T$ in the GS96 case.

Sensitivity to the photon parton densities can be also tested through the ratio of the resolved to the direct photon contributions. This is shown in Fig. for $d^2\sigma/d\eta dp_T^2$ in comparison with the results for the HERA collider. Again the results for THERA show a larger resolved cross-section and increased sensitivity to the form of the current parametrisations. The sensitivity is also large in the central $\eta$ region where there is, experimentally, a large acceptance.

3 MC predictions of dijet production with charm and beauty quarks

The dijet system can be formed from the production of a heavy quark pair such as in the boson-gluon fusion process. When the heavy quark is an active parton in the photon then the dijet system is formed from one heavy quark and a gluon. The other heavy quark in the event is produced at low transverse energy and forms part of the photon remnant.

A natural variable to describe dijet production is the observable $x_{\gamma}^{obs}$, which is the fraction
Figure 5: The ratio of the resolved to the direct photon contribution of $e^+e^- \rightarrow e^+e^- c/\bar{c} X$ (for $d^2\sigma/d\eta dp_T^2$) for $p_T=10$ GeV calculated in LO with the CTEQ5L parton parametrisation of the proton and three various LO parton parametrisations of the photon in the massless (VFNS) scheme. A) HERA, B) THERA collider.

of the photon’s energy producing the two jets of highest transverse energy \[10\]:

$$x_{\gamma}^{\text{obs}} = \frac{E_T^{\text{jet1}} \text{e}^{-\eta_{\text{jet1}}} + E_T^{\text{jet2}} \text{e}^{-\eta_{\text{jet2}}}}{2yE_e}, \quad (2)$$

where $\eta_{\text{jet}}$ is the pseudorapidity of the jet and $E_e$ is the electron energy and $y$ the fraction of the electron’s energy carried by the photon.

Due to the increase in the beam energy, there is a corresponding order of magnitude extension in the minimum $x_{\gamma}^{\text{obs}}$. This is shown in Fig. 3 in which two THERA scenarios (with the electron beam energy $E_e = 250$ GeV and $E_e = 400$ GeV) are compared with HERA. A greatly increased cross-section possible at THERA over that at HERA for low-$x_{\gamma}^{\text{obs}}$, particularly in beauty production, is seen. Realistic scenarios for the cuts on the jet quantities have been made of transverse energy $E_T^{\text{jet1,2}} > 10.8$ GeV and pseudorapidity $\eta_{\text{jet}} < 2.5$. The distribution is peaked at high-$x_{\gamma}^{\text{obs}}$, consistent with direct photon processes, but has a significant cross-section at low-$x_{\gamma}^{\text{obs}}$ arising from resolved photon events.

Charm and beauty production at a $\gamma p$ collider has also been considered and compared with the nominal $ep$ scenario for THERA. The photon beam energy is assumed to be $0.8E_e$, i.e. 200 GeV assuming an electron beam of energy 250 GeV. The predictions for the $ep$ and $\gamma p$ options with the same jet cuts are shown in Fig. 4. The cross-section prediction for the $\gamma p$ option is a factor of $\sim 25$ higher than the nominal $ep$ option. This factor arises simply from the Weizsäcker-Williams flux associated with the electron.

Further requirements can be made such that the kinematic range closely corresponds to what could be measured. Therefore the observation of a final state muon from the semi-leptonic decay of a beauty quark is imposed. The momentum and angular requirements imposed on the muon are typical of those at HERA. Considering jets of slightly lower transverse energy ($E_T^{\text{jet1,2}} > 7.6$ GeV), the effect on the low-$x_{\gamma}^{\text{obs}}$ component of pseudorapidity cut is shown in Fig. 5. It can be seen that for a pseudorapidity cut of $\eta_{\text{jet}} > -1$, the direct peak at high-$x_{\gamma}^{\text{obs}}$
Figure 6: The differential cross-section, $d\sigma/d\log_{10}(x_{\gamma^{obs}})$ for (a) charm and (b) beauty in dijet photoproduction at HERA and THERA as predicted by the HERWIG MC. The dashed and solid lines show THERA with an electron energy of 400 GeV and 250 GeV respectively and the dot-dashed lines indicate the expectation from HERA. The kinematic range is the same in all three cases, namely, $Q^2 < 1$ GeV$^2$, with two jets, $E_{T}^{jet1,2} > 10, 8$ GeV and $\eta^{jet} < 2.5$.

Figure 7: The differential cross-section, $d\sigma/d\log_{10}(x_{\gamma^{obs}})$ for (a) charm and (b) beauty in dijet photoproduction at for $\gamma p$ and $ep$ options at THERA as predicted by the HERWIG MC. The solid lines show THERA with an electron energy of 250 GeV and the dashed lines the expectation with an photon energy of 200 GeV. The kinematic range is the same in all three cases, namely, two jets, $E_{T}^{jet1,2} > 10, 8$ GeV and $\eta^{jet} < 2.5$. 
is drastically reduced with respect to a cut of $\eta^{\text{jet}} > -2$. This demonstrates that by applying a cut of $\eta^{\text{jet}} > -1$ interactions of almost exclusively the resolved photon are being probed.

This rather tight restriction on the pseudorapidity of the jets of $-1 < \eta^{\text{jet}} < 2$ is imposed and the sensitivity of the cross-section to the current parametrisations of the photon structure function investigated for THERA. In Fig. 8 predictions are shown for events where a beauty quark decays into a muon. Predictions are shown using both HERWIG [11] and PYTHIA [12] MC generators for four different LO photon PDFs. At values of $x_{\gamma}^{\text{obs}}=0.1$, differences between the four parametrisations of up to 40% are seen. The predictions from GRV and GS96 generally have the largest cross-sections at low-$x_{\gamma}^{\text{obs}}$ and also rise more quickly. The large difference in the PYTHIA and HERWIG MC predictions comes mainly from the different default treatments of $\alpha_s$, different scales and hadronisation and the use of massive matrix elements in HERWIG and massless in PYTHIA for the generation of flavour-excitation processes.

![Figure 8: The differential cross-sections, (a) $d\sigma/dx_{\gamma}^{\text{obs}}$ and (b) $d\sigma/d\log_{10}x_{\gamma}^{\text{obs}}$ for beauty in dijet photoproduction at THERA as predicted by the HERWIG MC. The events are selected in the range, $Q^2 < 1$ GeV$^2$, $0.2 < y < 0.85$ with two jets of transverse energy, $E_{T1,2} > 7, 6$ GeV. The points represent when the jets are restricted to $-1 < \eta^{\text{jet}} < 2$ and the solid lines when the jets are restricted to $-2 < \eta^{\text{jet}} < 2$. A muon in the final state has also been required with transverse momentum, $p_T^\mu > 2$ GeV and $|\eta^\mu| < 2$.](image-url)

4 Summary

It has been shown that the photoproduction of heavy quarks at THERA has a much increased cross-section relative to HERA. With the expected luminosity of about 100 pb$^{-1}$/year stringent tests of pQCD could be performed. It has also been shown that the cross-sections are sensitive to the structure of the photon, with the current parametrisations differing by significant amounts. The THERA collider also compares favourably with other current and planned machines studying heavy quark production, with the $\gamma p$ mode for THERA providing the largest cross-section.
Figure 9: The differential cross-sections, (a) $d\sigma/dx_{\gamma}^{\text{obs}}$ and (b) $d\sigma/d\log_{10}x_{\gamma}^{\text{obs}}$ for beauty in dijet photoproduction at THERA as predicted by the HERWIG MC. The differential cross-sections, (c) $d\sigma/dx_{\gamma}^{\text{obs}}$ and (d) $d\sigma/d\log_{10}x_{\gamma}^{\text{obs}}$ for beauty in dijet photoproduction at THERA as predicted by the PYTHIA MC. Predictions for four different PDFs are shown; GS96-LO (open circles), GRV-LO (solid circles), SaS-1D (stars) and SaS-2D (diamonds).
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References

[1] M. Glück, E. Reya and A. Vogt, Phys. Rev. D 46 (1992) 1973.
[2] C. Adloff at al., Euro. Phys. J. C 10 (1999) 363.
[3] H. L. Lai et al., Euro. Phys. J. C 12 (2000) 375.
[4] I. F. Ginzburg, G. L. Kotkin, V. G. Serbo and V. I. Telnov, Nucl. Instr. and Meth. 205 (1983) 47;
   I. F. Ginzburg, G. L. Kotkin, S. L. Panfil, V. G. Serbo and V. I. Telnov, Nucl. Instr. and Meth. 219 (1984) 5.
[5] V. I. Telnov, Nucl. Instr. and Meth. A 294 (1990) 72.
[6] B. A. Kniehl, M. Kramer, G. Kramer and M. Spira, Phys. Lett. B 356 (1995) 539.
[7] L. A. Gordon and J. K. Storrow, Nucl. Phys. B489 (1997) 405.
[8] G. A. Schuler and T. Sjöstrand, Z. Phys. C 68 (1995) 607.
[9] P. Jankowki, M. Krawczyk and A. De Roeck, To be published in the proceedings of Workshop on the Development of Future Linear Electron-Positron Colliders for Particle Physics Studies and for Research Using Free Electron Lasers, Lund, Sweden, 23-26 Sep 1999, Rolf Heuer, Francois Richard and Peter Zerwas Eds., hep-ph/0002169; and in preparation.
[10] ZEUS Collaboration, M. Derrick et al., Phys. Lett. B 348 665 (1995)
[11] G. Marchesini et al., Comp. Phys. Commun. 67 (1992) 465.
[12] H.-U. Bengtsson and T. Sjöstrand, Comp. Phys. Commun. 46 (1987) 43.