PRODUCTION OF CHARM WITH A PHOTON at $p\bar{p}$ COLLIDERS $^a$

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The two particle inclusive cross section for the reaction $p + \bar{p} \to \gamma + c + X$ is studied in perturbative quantum chromodynamics at order $O(\alpha_s^2)$. Differential distributions are provided for various observables, and a comparison is made with preliminary data from the CDF collaboration.

1 Introduction

The CDF Collaboration are analyzing data on prompt photon production in association with charm decay products such as $e^\pm$, $\mu^\pm$, or $D^\pm$. This two-particle inclusive reaction is particularly interesting because it offers the possibility of a detailed study of the underlying QCD dynamics such as, e.g., rapidity correlations. In addition the data may provide a direct measurement of the charm quark density of the proton due to the dominance of the $cg$ scattering process.

We completed two next-to-leading order perturbative QCD calculations of the reaction $p + \bar{p} \to \gamma + c + X$ at high energy. In these calculations two different techniques were used in performing the phase-space integrals. In the first, purely analytical techniques were used. In the second approach, we used a combination of analytical and Monte Carlo techniques, which is more flexible and allows implementation of isolation cuts and other experimentally relevant selections. To warrant use of perturbation theory and the massless charm approximation, we limited our considerations to values of transverse momenta of the photon and charm quark $p_T^{\gamma,c} > 10$ GeV. In these calculations we consider and include hard scattering processes in which the charm quark is a constituent of the incident hadrons e.g., $cg \to \gamma cX$. Details of these calculations can be found in the above references.

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We recently completed a different calculation of this reaction in which we included a finite charm quark mass explicitly. This calculation, which should be valid for \( p_{T} \leq 10 \text{ GeV} \), was done in leading order QCD \( (O(\alpha_s^2)) \). In this case the only subprocesses contributing to the reaction are those in which the charm quark is produced in the hard scattering reaction, namely \( gg \rightarrow c\bar{c}\gamma \) and \( q\bar{q} \rightarrow c\bar{c}\gamma \). There are no collinear or soft singularities at this order and no fragmentation contributions to the reaction. The integration over the final state phase space could therefore be done numerically with Monte Carlo routines and photon isolation cuts could be implemented.

2 Numerical Results

Our results are presented at a center-of-mass energy \( \sqrt{s} = 1.8 \text{ TeV} \). Renormalization/factorization scales are taken as \( \mu = p_{T}^2 \). We sum over charm and anticharm production throughout. Some results are presented as distributions in the variable \( z = \frac{p_{T}^c - p_{T}^\gamma}{(p_{T}^\gamma)^2} \), for finite bin widths of \( z \). In Fig.1a the net lowest order contribution for the massless calculation is shown as a function of \( z \) at \( p_{T}^\gamma = 15 \text{ GeV} \) and for a bin size \( \Delta z = 0.2 \). The lowest order cross section is made up of the lowest order direct term \( cg \rightarrow \gamma c \), which is proportional to \( \delta(1-z) \) and provides the peak at \( z = 1 \), plus the various photon fragmentation contributions which contribute in the region \( z \geq 1 \). The most significant feature of this curve is that there is no contribution to the cross section in the region \( z \leq 1 \). This unrealistic prediction shows the inadequacy of the lowest order predictions.
Fig. 1b shows the distribution in $z$ predicted by the next-to-leading order massless calculation. The next-to-leading order contributions serve to lower the peak at $z = 1$, and they broaden the distribution. The cross section is finite at all values of $z$, closer to the situation observed in experiments. In addition, in Fig. 1b we display contributions from the most important subprocesses. The $cg$ initiated process dominates the cross section, but there are important contributions from the $gg$ and $cq$ initiated process in the low $p_T^\gamma$ region. Predicted distributions in $p_{T}^{\gamma}$, $p_{T}^{\mu}$ and rapidities may be found in 2, 3.

In Fig. 2a we show the $z$ distribution for the same kinematic variables as above but now for the leading order massive calculation with various choices for the charm quark mass. For comparison the full massless next-to-leading order results are also displayed. Although the massive calculation is done in leading order, the contributing subprocesses are two-to-three scattering processes, and they contribute in the region $z < 1$. In this sense the massive calculation gives a more realistic result than the corresponding massless calculation. On the other hand it clearly predicts a smaller cross section than the next-to-leading order massless calculation. We note, however, that the next-to-leading order contributions to heavy quark production are known to provide significant increases in the predicted yields 4. Fig. 2a also demonstrates the sensitivity to the choice for the charm mass particularly in the region around $z = 1$. This is the region in which the finite charm mass regulates the initial state collinear divergences.

In Fig. 2b we compare our results to CDF data 5 for photon plus $\mu^\pm$ production. The three upper points are obtained from the Monte Carlo event generator Pythia whereas the lower point is that given by our theoretical calculation. The Pythia cross sections lie substantially below the data whereas our cross section exceeds the data but somewhat closer to it.

3 Conclusions

We presented the results of three calculations of the inclusive production of a prompt photon in association with a heavy quark. Two analyses are done at next-to-leading order in perturbative QCD in the massless charm framework, and one calculation in leading order QCD in the massive charm framework. Our results in the massless cases agree quantitatively, as they should, but the combination of analytic and Monte Carlo methods is more versatile. A comparison of our next-to-leading predictions with the preliminary CDF data shows reasonable agreement.
Figure 2: (a) $z$ distribution of the leading order massive calculation for various values of the charm mass. The next-to-leading order massless results are also shown. (b) Ratio of the measured cross section to that predicted by theory for various final state charm decay products.

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References

1. CDF Collaboration, F. Abe et al, Fermilab Report FERMILAB Pub-96/152E, Submitted to Phys. Rev. Lett.
2. E. L. Berger and L. E. Gordon, Argonne report ANL-HEP-PR-95-36 (hep-ph/9512343), Phys. Rev. D (in press), and references therein.
3. B. Bailey, E. L. Berger and L. E. Gordon, Argonne report ANL-HEP-PR-95-87 (hep-ph/9602373), Phys. Rev. D (in press), and references therein.
4. P. Nason, S. Dawson and R.K. Ellis, Nucl. Phys. B303 (1988) 607; B327 (1989) 49; B335 (1990) 260 (E). W. Beenakker, H. Kuijif, W.L. van Neerven and J. Smith, Phys. Rev. D40 (1989) 54; W. Beenakker, W.L. van Neerven, R. Meng, G.A. Schuler and J. Smith, Nucl. Phys. B351 (1991) 507.
5. S. Kuhlmann, CDF Collaboration, private communication.