Measurement of the differential $\gamma + c$-jet cross section and the ratio of differential $\gamma + c$ and $\gamma + b$ cross sections in $pp$ collisions at $\sqrt{s} = 1.96$ TeV

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We present measurements of the differential cross section $d\sigma/dp_T^\gamma$ for the associated production of a $c$-quark jet and an isolated photon with rapidity $|y|<1.0$ and transverse momentum $30 < p_T^\gamma < 300$ GeV. The $c$-quark jets are required to have $|y^{\text{jet}}|<1.5$ and $p_T^{\text{jet}}>15$ GeV. The ratio of differential cross sections for $\gamma + c$ to $\gamma + b$ production as a function of $p_T^\gamma$ is also presented. The results are based on data corresponding to an integrated luminosity of $8.7$ fb$^{-1}$ recorded with the D0 detector at the Fermilab Tevatron $p\bar{p}$ Collider at $\sqrt{s}=1.96$ TeV. The obtained results are compared to next-to-leading order perturbative QCD calculations using various parton distribution functions, to predictions based on the $k_T$-factorization approach, and to predictions from the SHERPA and PYTHIA Monte Carlo event generators.

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1 In hadron-hadron collisions high-energy photons are mainly produced directly in a hard parton scattering process. For this reason, and due to their pointlike electromagnetic coupling to the quarks, they provide a clean probe of parton-level dynamics. Photons in association with a charm (c) quark are produced primarily through the Compton-like scattering process $gc \rightarrow \gamma c$, which dominates up to photon transverse momenta with respect to the beam axis of $p_T^\gamma \approx 70-80$ GeV, and through quark antiquark annihilation, $gq \rightarrow \gamma g \rightarrow \gamma c\bar{c}$, which dominates at higher $p_T^\gamma$. Inclusive $\gamma + c$ production may also originate in processes like $gg \rightarrow c\bar{c}$ or $cg \rightarrow c\bar{c}$, where the fragmentation of a final state $c$-quark or gluon produces a photon. Photon isolation requirements substantially reduce the contributions from these processes. Measurements of the $\gamma + c$-quark jet differential cross section as a function of $p_T^\gamma$ improve our understanding of the underlying production mechanism and provide useful input for the $c$-quark parton distribution functions (PDFs) of the colliding hadrons.

In this Letter, we present measurements of the inclusive $\gamma + c$-jet production cross sections using data collected from June 2006 to September 2011 with the D0 detector in $p\bar{p}$ collisions at $\sqrt{s}=1.96$ TeV which correspond to an integrated luminosity of $8.7 \pm 0.5$ fb$^{-1}$.

The cross section is measured differentially as a function of $p_T^\gamma$ for photons within rapidities $|y|<1.0$ and $30 < p_T^\gamma < 300$ GeV, while the $c$-jet is required to have $|y^{\text{jet}}|<1.5$ and $p_T^{\text{jet}}>15$ GeV. In comparison to our previous $\gamma + c$-jet measurement, we now retain all events having at least one jet originating from a charm quark, as opposed to considering only the events in which the charm jet candidate is the jet with highest $p_T$. To increase the signal yield and study a trend in the data/theory ratio observed in Ref. [2], we have extended the rapidity region from $|y^{\text{jet}}|<0.8$ to $|y^{\text{jet}}|<1.5$ and combine regions with positive and negative products of rapidities, $\gamma y^{\text{jet}}$. In addition, an increased integrated luminosity by about a factor of nine allows the $p_T^\gamma$ range to be extended to higher values.

The data set and event selections used in our measurement are similar to those used in the recently published measurement of the $\gamma + b$-jet differential cross section [3]. However, because of the difficulty in discriminating $c$ jets...
from light jets, this measurement adopts a different strategy for the estimation of the c-jet fraction. Here we apply a significantly more stringent requirement for selecting heavy flavor jets (originating from c and b quarks) in order to suppress the rates of light jets (originating from light quarks or gluons) by an additional factor of $2.5 - 3.0$. This small residual contribution of light jets is then subtracted from the selected data events prior to performing to extract the c-jet fraction. Using this event selection criteria, we reproduce the results for the $\gamma + \text{jet}$ cross section with 3% systematic uncertainty. The electromagnetic calorimeter with loose shower shape requirements is 0% for photon candidates, where it is 96% for photon candidates. The jet acceptance with respect to $p_T$ varies between 91% and 100% in different $p_T$ bins. Uncertainties on the acceptance due to the jet energy scale, jet energy resolution, and the difference between results obtained with Sherpa and Pythia are in the range of $(1 - 4)%$. A set of criteria is imposed to have sufficient information to classify the jet as a heavy-flavor candidate: the jet is required to have at least two associated tracks with $p_T > 0.5$ GeV with at least one hit in the SMT, and at least one of these tracks must have $p_T > 1.0$ GeV. These criteria have an efficiency of about 90%.

To enrich the sample with heavy-flavor jets, a neural net based b-tagging algorithm (b-NN) is applied. It exploits the longer lifetimes of b-flavored hadrons in comparison to their lighter counterparts, after the rejection of long-lived $K_s^0$ and $\Lambda$ decays. The inputs to the b-NN combine information from the impact parameter of displaced tracks and the topological properties of secondary vertices reconstructed in the jet to provide a continuous output value that tends towards one for b jets and zero for light-quark jets. Events are required to contain at least one jet satisfying b-NN output $> 0.7$. This b-tagging selection suppresses light jets to less than 5% of the heavy-flavor enhanced sample. The efficiency for b and c jets to satisfy the b-tagging requirements in the simulation is scaled by the data-to-Monte Carlo (MC) correction factors parametrized as a function of jet $p_T$ and $\eta$. Depending on $p_T$, the selection efficiency for this requirement is $(8 - 10)%$ for c-jets with relative
systematic uncertainties of $(6 - 23)$%, caused by uncertainty on the data-to-MC correction factors. The maximum difference between the efficiencies for $c$-jets arising from the Compton-like and annihilation subprocesses is about 10%.

The relative rate of remaining light jets ("light/all") in the sample after the final selection is estimated using SHERPA and PYTHIA $\gamma$+jet events, taking into account the data-to-MC correction factors as described in Ref. [14]. The light jet rates predicted by PYTHIA and SHERPA agree within 5%. The central predictions are taken from SHERPA, which agrees with measured $\gamma$+jet [15, 16] and $\gamma + b$-jet [3] cross sections within $(10 - 25)$%.

After application of all selection requirements, 130,875 events remain. We estimate the photon purity using an artificial neural network discriminant [5]. The distribution of the output of this discriminant ($O_{\text{NN}}$) is fitted to a linear combination of templates for photons and jets obtained from simulated $\gamma$ + jet and dijet samples, respectively. An independent fit is performed in each $p_T$ bin. It yields photon purities between 62% and 99%, which are close to those obtained in Ref. [3]. Their systematic uncertainties are of a comparable magnitude, (5–9)%.

The invariant mass of all charged particles associated with a displaced secondary vertex in a jet, $M_{\text{SV}}$, is a powerful variable to discriminate $c$ from $b$ jets. Since the $M_{\text{SV}}$ templates for light and $c$-jets after application of tight $b$-tagging requirements are quite close to each other, we first subtract the remaining small fraction (1–5%) of $b$ light jets from the data. Then $c$-jet fraction is determined by fitting $M_{\text{SV}}$ templates for $c$ and $b$ jets to the data. The results of this discriminant fitted templates to $c$ and $b$ jets are obtained from PYTHIA samples of $\gamma + b$-jet and $\gamma + c$-jet events, respectively, and are uncorrelated from bin to bin. The templates generated using SHERPA. The templates for jets arising from the Compton-like and annihilation subprocesses are also similar to each other.

The result of a maximum likelihood fit to the $M_{\text{SV}}$ templates, normalized to the number of events in data, is shown in Fig. 1 for the $50 < p_T^\gamma < 60$ GeV bin as an example. Fits in the other $p_T^\gamma$ bins are of similar quality. As shown in Fig. 2, the estimated $c$-jet fraction obtained from the fits in the final selected heavy-flavor sample after subtraction of the light-jet component drops with increasing $p_T^\gamma$, on average, from about 52% to about 40%, increasing $p_T^\gamma$, on average, from about 52% to about 40%, increasing $p_T^\gamma$, on average, from about 52% to about 40%.

The corresponding fit uncertainties range between (4–25)%, increasing towards higher $p_T^\gamma$, and are determined by the limited data statistics. Since the fits are performed independently in each $p_T^\gamma$ bin, these uncertainties are uncorrelated from bin to bin. Additional systematic uncertainties are estimated by varying the relative rate of light jets by ±50% and by considering the differences in the light jet predictions from SHERPA and PYTHIA event generators. These two sources lead to uncertainties on the $c$-jet fraction of about (5–9)% and 6%, respectively.

Systematic uncertainty on the measured cross sections due to the $b$-NN selection is estimated by performing the measurement with looser $b$-NN selections: requiring $b$-NN output $> 0.3$ or $> 0.5$ instead of 0.7. In both cases, this significantly increases the light-jet rate and also changes the $c$ and $b$-jet fractions, resulting in a variation of the $\gamma + c$-jet cross section of $\leq 7$%. This variation is taken as a systematic uncertainty on the cross section.

The data, corrected for photon and jet acceptance, reconstruction efficiencies and the admixture of background events, are presented at the particle level [12] for comparison with predictions by unfolding the data for effects of detector resolution.

The differential cross sections of $\gamma + c$-jet production are extracted in nine bins of $p_T^\gamma$. They are listed in Table II and are shown in Fig. 3. The data points are plotted at the values of $p_T^\gamma$ for which the value of a smooth function describing the dependence of the cross section on $p_T^\gamma$ equals the averaged cross section in the bin.

The statistical uncertainty of the results ranges from 2% in the first $p_T^\gamma$ bin to 11% in the last $p_T^\gamma$ bin. The total systematic uncertainty varies between 14% and 42% across these bins. The main sources of uncertainty at low $p_T^\gamma$ are due to the photon purity (up to 8%), the c-jet fraction (10 – 33%), and the luminosity (6%) [2]. The total systematic uncertainties ($\delta_{\text{sys}}$) and the bin-to-bin uncorrelated components ($\delta_{\text{unc}}^{\text{sys}}$) are shown in Table II.

The differential cross sections of $\gamma + c$-jet production at 25% are shown in Fig. 3. The data points are plotted at the values of $p_T^\gamma$ for which the value of a smooth function describing the dependence of the cross section on $p_T^\gamma$ equals the averaged cross section in the bin [17].

The statistical uncertainty of the results ranges from 2% in the first $p_T^\gamma$ bin to 11% in the last $p_T^\gamma$ bin. The total systematic uncertainty varies between 14% and 42% across these bins. The main sources of uncertainty at low $p_T^\gamma$ are due to the photon purity (up to 8%), the c-jet fraction (10 – 33%), and the luminosity (6%) [2]. The total systematic uncertainties ($\delta_{\text{sys}}$) and the bin-to-bin uncorrelated components ($\delta_{\text{unc}}^{\text{sys}}$) are shown in Table II.

Next-to-leading order (NLO) perturbative QCD pre-
predictions of order $\mathcal{O}(\alpha_s^2)$ [16, 18], with the renormalization scale $\mu_R$, factorization scale $\mu_F$, and fragmentation scale $\mu_f$ all set to $p_T^\gamma$, are given in Table I. The uncertainty from the scale choice is estimated through a simultaneous variation of all three scales by a factor of two, i.e., for $\mu_R,F,f = 0.5p_T^\gamma$ and $2p_T^\gamma$, and is found to be similar to those for $\gamma + b$-jet predictions ($5 - 30\%$), being larger at higher $p_T^\gamma$. The NLO predictions utilize CTEQ6.6M PDFs [10] and are corrected for non-perturbative effects of parton-to-hadron fragmentation and multiple parton interactions. The latter are evaluated using SHERPA [10] and PYTHIA MC samples generated using their default settings [11]. The overall corrections vary within 0.90 - 0.95 with an uncertainty of $\lesssim 2\%$ assigned to account for the difference between the two MC generators.  

The predictions based on the $k_T$-factorization approach [20, 21] and unintegrated parton distributions [22] are also given in Table I. The resummation of gluon diagrams with gluon transverse momentum ($k_T$) above a scale $\mu$ of order 1 GeV, leads to a broadening of the photon transverse momentum distribution in this approach [20]. The scale uncertainties on these predictions vary from about $-28\%$/$+31\%$ at $30 < p_T^\gamma < 40$ GeV to
about $+14\%$/$+5\%$ in the last $p_T^\gamma$ bin.

Table I also contains predictions from the \textsc{pythia} \[11\] event generator with the \textsc{cteq}6.6 \[19\] PDF set. It includes only $2 \rightarrow 2$ matrix elements (ME) with $g \gamma \rightarrow c \bar{c}$ and $q \bar{q} \rightarrow \gamma g$ scatterings (defined at LO) followed by $g \rightarrow c \bar{c}$ in the splitting in the parton shower (PS). We also provide predictions by \textsc{sherpa} \[10\] with the \textsc{cteq}6.6M PDF set \[13\]. Matching between the MEs and the PS jets follows the prescription given in Ref. \[13\], with the matching scale taken to be $15$ GeV. Systematic uncertainties are estimated by varying the ME-PS matching scale by $\pm 5$ GeV around the chosen central value \[23\], resulting in a $\pm 7\%$ cross section variation.

All theoretical predictions are obtained using the photon isolation requirement of $E_T^{iso} < 2.5$ GeV. The predictions are compared to data in Fig. \[8\] as a function of $p_T^\gamma$. The ratios of data over the NLO QCD calculations \[35\] and of the various theoretical predictions to the NLO QCD calculations are presented in Fig. \[4\]. The NLO predictions with \textsc{cteq}6.6M agree with MSTW2008 \[24\] and ABKM09 \[25\] within $10\%$. Parameterizations for models containing intrinsic charm (IC) have been included in \textsc{cteq}6.6c \[26\]. Here we consider the BHPS IC model \[27\] and the sea-like model in which the charm PDF is sea-like, similar to that of the light-flavor sea quarks. The NLO QCD predictions based on these intrinsic charm models are normalized to the standard \textsc{cteq} predictions and are also shown in Fig. \[3\]. Both non-perturbative intrinsic charm models predict a higher $p_T^\gamma$ region, which is dominated by the annihilation process $q \bar{q} \rightarrow \gamma g$ (with $q \rightarrow c \bar{c}$), and resummation of diagrams with additional gluon radiation. In addition, the underestimate of the rates for diagrams with $q \rightarrow c \bar{c}$ splittings may result in lower theoretical predictions of cross sections as suggested by LEP \[30\], LHCb \[31\] and ATLAS \[32\] results. The prediction from the $k_T$-factorization approach is in better agreement with data at $p_T^\gamma > 120$ GeV. However, it underestimates the cross section in the low and intermediate $p_T^\gamma$ region. The $\gamma +c$-jet cross section as predicted by \textsc{sherpa} becomes higher than the NLO QCD prediction at large $p_T^\gamma$, but is still lower than the measured values. It has been suggested that combining NLO parton-level calculations for the ME with PS predictions \[33\] will improve the description of the data \[34\].

In addition to measuring the $\gamma +c$-jet cross-section, we also obtain results for the $\gamma +b$-jet cross section using the new tight $b$-NN selection. The values of the obtained $\gamma +b$-jet cross section agree within $10\%$ (i.e. within uncertainties) with the published results \[5\] obtained with a looser $b$-NN selection. We use them to calculate the ratio $\sigma(\gamma +c)/\sigma(\gamma +b)$ in bins of $p_T^\gamma$. In this ratio, many experimental systematic uncertainties cancel. Also, theory predictions of the ratio are less sensitive to the scale uncertainties, and effects from missing higher-order terms that impact the normalizations of the cross sections. The remaining uncertainties are caused by largely $(65 - 67\%)$ correlated uncertainties coming from the fitting of $c$-jet and $b$-jet $M_{SV}$ templates to data, and by other uncertainties on the $c$-jet fractions discussed above. The systematic uncertainties on the ratio vary within $(6 - 26\%)$, being largest at high $p_T^\gamma$. Theoretical scale uncertainties, estimated by varying scales by a factor of two (to $\mu_{R,F,I} = 0.5p_T^\gamma$ and $2p_T^\gamma$) in the same way for $\sigma(\gamma +c)$ and $\sigma(\gamma +b)$ predictions, are also significantly reduced. Specifically, residual scale uncertainties are typically $\lesssim 10\%$ for the $k_T$-factorization approach and $\lesssim 4\%$ for NLO QCD, which indicates a much smaller dependence of the ratio on the higher-order corrections.
TABLE II: The $\sigma(\gamma + c)/\sigma(\gamma + b)$ cross section ratio in bins of $p_T^\gamma$ for $|y| < 1.0$, $p_T^{jet} > 15$ GeV and $|y^{jet}| < 1.5$ together with statistical uncertainties ($\delta_{stat}$), total systematic uncertainties ($\delta_{syst}$), and the uncorrelated component of $\delta_{syst}$ ($\delta_{unc}$). The column $\delta_{tot}$ shows total experimental uncertainty obtained by adding $\delta_{stat}$ and $\delta_{syst}$ in quadrature. The last four columns show theoretical predictions obtained using NLO QCD, $k_T$-factorization, PYTHIA and SHERPA event generators.

| $p_T^\gamma$ bin (GeV) | (p_T^{jet}) (GeV) | Data $\delta_{stat}$ (%) | $\delta_{syst}(\delta_{unc})$ (%) | $\delta_{tot}$ (%) | $\sigma(\gamma + c)/\sigma(\gamma + b)$ | NLO QCD | $kT$ fact. | PYTHIA | SHERPA |
|------------------------|------------------|--------------------------|-----------------------------|-----------------|-----------------------|---------|-----------|--------|---------|
| 30 – 40                | 34.2             | 5.83                     | 6 (3)                       | 6               | 5.81                  | 4.30    | 5.10      | 6.17   |
| 40 – 50                | 44.3             | 5.03                     | 6 (3)                       | 6               | 5.28                  | 4.01    | 4.97      | 5.28   |
| 50 – 60                | 54.3             | 4.90                     | 7 (3)                       | 7               | 4.79                  | 3.83    | 4.66      | 4.79   |
| 60 – 70                | 64.5             | 4.55                     | 8 (4)                       | 8               | 4.37                  | 3.91    | 4.34      | 4.21   |
| 70 – 90                | 78.1             | 4.97                     | 8 (4)                       | 8               | 3.83                  | 3.88    | 3.99      | 3.54   |
| 90 – 110               | 98.6             | 4.22                     | 9 (6)                       | 9               | 3.19                  | 3.83    | 3.59      | 2.95   |
| 110 – 140              | 122              | 3.73                     | 10 (6)                      | 11              | 2.60                  | 3.86    | 3.00      | 2.50   |
| 140 – 180              | 156              | 4.34                     | 13 (10)                     | 14              | 2.12                  | 3.53    | 2.44      | 2.19   |
| 180 – 300              | 216              | 3.38                     | 26 (22)                     | 27              | 1.73                  | 4.04    | 1.98      | 1.93   |

FIG. 5: (Color online) The ratio of $\gamma + c$-jet and $\gamma + b$-jet production cross sections for data together with theoretical predictions as a function of $p_T^\gamma$. The uncertainties on the data include both statistical (inner error bar) and total uncertainties (full error bar). Predictions given by $k_T$-factorization [24, 21], SHERPA [10] and PYTHIA [11] are also shown. The PYTHIA predictions with a contribution from the annihilation process increased by a factor of 1.7 are shown as well. The BHPS model agrees with data at $p_T^\gamma > 80$ GeV, while the sea-like model is significantly beyond the range of data points. BHPS model would better describe the ratio to data with a small shift in normalization. As with the $\gamma + c$-jet measurement, the $\sigma(\gamma + c)/\sigma(\gamma + b)$ ratio can also be better described by larger $g \to cc$ rates than those used in the current NLO QCD, SHERPA and PYTHIA predictions. To test this, we have increased the rate of the annihilation process (where $c$ jet is always produced due to $g \to cc$ splitting) in the PYTHIA predictions. The best description of data is achieved by increasing the rates by a factor of 1.7 with $\chi^2/\text{ndf} \approx 0.7$ (compared to $\chi^2/\text{ndf} = 4.1$ if such a factor is unity). However, according to our estimates using the signal events simulated with SHERPA, there are also about (10–35)% (higher for larger $p_T^{\gamma}$) events with two $c$-jets. Assuming that one jet is coming from gluon initial state radiation followed by $g \to cc$ splitting, the required overall correction factor would be smaller by about (8–24)%. In conclusion, we have measured the differential cross section of $\gamma + c$-jet production as a function of $p_T^\gamma$ at the Fermilab Tevatron $p\bar{p}$ collider. Our results cover the kinematic range $30 < p_T^\gamma < 300$ GeV, $p_T^{jet} > 15$ GeV, $|y| < 1.0$, and $|y^{jet}| < 1.5$. In the same kinematic region, and in the same $p_T^{\gamma}$ bins, we have measured the $\sigma(\gamma + c)/\sigma(\gamma + b)$ cross section ratio. None of the theoretical predictions considered give good description of the data in all $p_T^\gamma$ bins. Such a description might be achieved by including higher-order corrections into the QCD predictions, while at $p_T^{\gamma} \gtrsim 80$ GeV the observed difference from data may also be caused by an underestimated contribution from gluon splitting $g \to cc$ [30, 32] in the annihilation process or by contribution from intrinsic charm.
The presented results can be used for further development of theoretical models to understand production of high energy photons in association with heavy flavor jets.

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