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Measurement of the differential $\gamma + 2b$-jet cross section and the ratio $\sigma(\gamma + 2b$-jets)/$\sigma(\gamma + b$-jet) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

D0 Collaboration

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In hadronic collisions, high-energy photons ($\gamma$) emerge unaltered from the hard parton–parton interaction and therefore provide a clean probe of the underlying hard-scattering dynamics [1]. Photons produced in these interactions (called direct or prompt) in association with one or more bottom ($b$-)quark jets provide an important test of perturbative Quantum Chromodynamics (QCD) predictions at large hard-scattering scales $Q$ and over a wide range of parton momentum fractions. In addition, the study of these processes also provides information about the parton density functions (PDF) of $b$ quarks and gluons ($g$), which still have substantial uncertainties. In $p\bar{p}$ collisions, $\gamma + b$-jet events are produced primarily through the Compton process $gb \to \gamma b$, which dominates for low and moderate photon transverse momenta $(p_T^\gamma)$, and through quark–antiquark annihilation followed by $g \to b\bar{b}$ gluon splitting $q\bar{q} \to \gamma g \to \gamma b\bar{b}$, which dominates at high $p_T^\gamma$ [2,3]. The final state with $b$-quark pair production, $pp \to \gamma + b\bar{b}$, is mainly produced via $q\bar{q} \to \gamma b\bar{b}$ and $gg \to \gamma b\bar{b}$ scatterings [4]. The $\gamma + 2 b$-jet process is a crucial component of background in measurements of, for example, $tt\gamma$ coupling [5] and in some searches for new phenomena. A series of measurements involving $\gamma$ and $b$($c$)-quark final states have previously been performed by the D0 and CDF Collaborations [3,6–9].
In this measurement, we follow an inclusive approach by allowing the final state with any additional jet(s) on top of the studied b-quark jets. Inclusive $\gamma + 2$ b-jet production may also originate from partonic subprocesses involving parton fragmentation into a photon. However, using photon isolation requirements significantly reduces the contributions from such processes. Next-to-leading order (NLO) calculations of the $\gamma + 2$ b-jet production cross section, which includes all b-quark mass effects, have recently become available [4]. These calculations are based on the four-flavor number scheme, which assumes four massless quark flavors and treats the b quark as a massive quark not appearing in the initial state.

This letter presents the first measurement of the cross section for associated production of an isolated photon with a bottom quark pair in $p\bar{p}$ collisions. The results are based on data corresponding to an integrated luminosity of $8.7 \pm 0.5$ fb$^{-1}$ [10] collected with the D0 detector from June 2006 to September 2011 at the Fermilab Tevatron Collider at $\sqrt{s} = 1.96$ TeV. The large data sample and use of advanced photon and b-jet identification tools [11–13] enable us to measure the $\gamma + 2 b$-jet production cross section differentially as a function of $p_T^\gamma$ for photons with rapidities $|y^\gamma| < 1.0$ and transverse momenta $30 < p_T^\gamma < 200$ GeV, while the b jets are required to have $p_T^b > 15$ GeV and $|y^b| < 1.5$. This allows for probing the dynamics of the production process over a wide kinematic range not studied before in other measurements of a vector boson +b-jet final state. The ratio of differential cross sections for $\gamma + 2 b$-jet production relative to $\gamma + b$-jet production is also presented in the same kinematic region and differentially in $p_T^\gamma$. The measurement of the ratio of cross sections leads to cancellation of various experimental and theoretical uncertainties, allowing a more precise comparison with the theoretical predictions.

The D0 detector is a general purpose detector described in detail elsewhere [14]. The subdetectors most relevant to this analysis are the central tracking system, composed of a silicon microstrip tracker (SMT) and a central fiber tracker embedded in a 1.9 T solenoidal magnetic field, the central preshower detector (CPS), and the calorimeter. The CPS is located immediately before the inner layer of the central calorimeter and is formed of approximately one radiation length of lead absorber followed by three layers of scintillating strips. The calorimeter consists of a central section (CC) with coverage in pseudorapidity of $|\eta_{det}| < 1.1$ [14] and two end calorimeters (EC) extending coverage to $|\eta_{det}| = 4.2$, each housed in a separate cryostat, with scintillators between the CC and EC cryostats providing sampling of developing showers for $1.1 < |\eta_{det}| < 1.4$. The electromagnetic (EM) section of the calorimeter is segmented longitudinally into four layers (EMi, $i = 1$–4), with transverse segmentation into cells of size $\Delta \eta_{det} \times \Delta \phi_{det} = 0.1 \times 0.1$ (see footnote 14), except EM3 (near the EM shower maximum), where it is $0.05 \times 0.05$. The calorimeter allows for a precise measurement of the energy of electrons and photons, providing an energy resolution of approximately 4% (3%) at an energy of 30 (100) GeV. The energy response of the calorimeter to photons is calibrated using electrons from Z boson decays. Because electrons and photons interact differently in the detector material before the calorimeter, additional energy corrections as a function of $p_T^\gamma$ are derived using a detailed GEANT-based [15] simulation of the D0 detector response. These corrections are $\approx 2\%$ for photon candidates of $p_T^\gamma = 30$ GeV, and smaller for higher $p_T^\gamma$.

The data used in this analysis are required to satisfy D0 experimental data quality criteria that ensure the proper functioning of detector subsystems (calorimeter and tracking detectors are most important for this analysis) [14] during data-taking. The data is collected using a combination of triggers requiring a cluster of energy in the EM calorimeter with loose shower shape requirements. The trigger efficiency is $\approx 96\%$ for photon candidates with $p_T^\gamma = 30$ GeV and $100\%$ for $p_T^\gamma \geq 40$ GeV. Offline event selection requires a reconstructed $p\bar{p}$ interaction vertex [16] within 60 cm of the center of the detector along the beam axis. The efficiency of the vertex requirement is $\approx (96–98)\%$, depending on $p_T^\gamma$. The missing transverse momentum in the event is required to be less than 0.7$p_T^\gamma$ to suppress background from $W \to e\nu$ decays. Such a requirement is highly efficient ($\geq 98\%$) for signal events.

Photon candidates are identified in the D0 detector as isolated clusters of energy deposits in the calorimeter with significant energy in the EM calorimeter layers and no spatially-matched track in the tracking system. The detailed description of photon selection and isolation criteria can be found in Refs. [3, 6]. The photon selection efficiency and acceptance are calculated using samples of $\gamma + b$-jet events, generated with the SHERRA [17] and PYTHIA [18] Monte Carlo (MC) event generators. The samples are processed through a GEANT-based [15] simulation of the D0 detector. Simulated events are overlaid with data events from random $p\bar{p}$ crossings to properly model the effects of multiple $p\bar{p}$ interactions and noise in data. We ensure that the instantaneous luminosity distribution in the overlay events is similar to the data. The efficiency for photons to pass the identification criteria is (71–82)\% with relative systematic uncertainty of 3%.

For the $\gamma + n b$ measurement ($n = 1, 2$), at least n jets with $p_T^{jet} > 15$ GeV and $|y^{jet}| < 1.5$ are selected. Jets are reconstructed using the D0 Run II algorithm [19] with a cone radius of $R = 0.5$. A set of criteria is imposed to ensure that we have sufficient information to identify the jet as a heavy-flavor candidate: the jet is required to have at least two associated tracks with $p_T > 0.5$ GeV and at least one hit in the SMT, one of these tracks must also have $p_T > 1.0$ GeV. These criteria have an efficiency of about 90% for a b jet. Light jets (initiated by u, d and s quarks or gluons) are suppressed using a dedicated heavy-flavor (HF) tagging algorithm [13].

The HF tagging algorithm is based on a multivariate analysis (MVA) technique that combines information from the secondary vertex (SV) tagging algorithms and tracks impact parameter variables using an artificial neural network (NN) to define a single output discriminant, MVA$_{bb}$ [13]. This algorithm utilizes the longer lifetimes of HF hadrons relative to their lighter counterparts. The MVA$_{bb}$ has a continuous output value that tends towards one for b jet and zero for light jets. Events with at least two jets passing the MVA$_{bb} > 0.3$ selection are considered in the $\gamma + 2 b$-jet analysis. Depending on $p_T^\gamma$, this selection has an efficiency of ($13–21$)\% for two b jets with relative systematic uncertainties of (4–6)\%, primarily due to uncertainties on the data-to-MC correction factors [13]. Only (0.2–0.4)\% of light-jets are misidentified as b jets.

After application of all selection requirements, 3816 $\gamma + 2 b$-jet candidate (186,406 $\gamma + b$-jet candidate) events remain in the data sample. In these events, there are two main background sources: jets misidentified as photons and light-flavor jets mimicking HF jets. To estimate the photon purity, the $\gamma$–NN distribution in data is fitted to a linear combination of templates for photons and jets obtained from simulated $\gamma +$ jet and dijet samples. An independent fit is performed in each $p_T^\gamma$ bin, yielding photon fractions between 62\% and 90\%, as shown in Fig. 1. The main systematic uncertainty in the photon fractions is due to the fragmentation model implemented in PYTHIA [20]. This uncertainty is estimated by varying the production rate of $\pi^0$ and $\eta$ mesons by $\pm 50\%$ with respect to their

14 The polar angle $\theta$ and the azimuthal angle $\phi$ are defined with respect to the positive z axis, which is along the proton beam direction. Pseudorapidity is defined as $\eta = -\ln(tan(\theta/2))$. Also, $\eta_{det}$ and $\phi_{det}$ are the pseudorapidity and the azimuthal angle measured with respect, to the center of the detector.
plates consisting mainly of 2 b-jet and 2 c-jet events, as determined from MC simulation. The remaining jet flavor contributions in the sample (e.g., light+light-jets, light+b(c)-jets, etc.) are small and are subtracted from the data. The fractions of these rarer jet contributions are estimated from SHERPA simulation (which has been found to provide a good description of the data), and vary in the range (5–10)%. The difference in the values of these fractions obtained from SHERPA and PYTHIA, (2–4)%, is assigned as a systematic uncertainty on the background estimate. The fraction of 2 b-jet events are determined by performing a two-dimensional (corresponding to the 2 b-jet candidates) maximum likelihood fit of $D_{\text{ML}}$ distributions of 2 jet events in data using the corresponding templates for 2 b-jets and 2 c-jets. These jet flavor templates are obtained from MC simulations. As an example, the result of one of these maximum likelihood fits to $D_{\text{ML}}$ templates is presented in Fig. 2 (with $\chi^2/n\text{df} = 6.80/5$ for data/MC agreement). This shows the one-dimensional projection onto the highest $p_T$ jet $D_{\text{ML}}$ axis of the 2D fit, normalized to the number of events in data, for photons with $30 < p_T^{\gamma} < 40$ GeV. An independent fit is performed in each $p_T^{\gamma}$ bin, resulting in extracted fractions of 2 b-jet events between 76% and 87%, as shown in Fig. 3. The relative uncertainties of the estimated 2 b-jet fractions range from 5% to 14%, increasing at higher $p_T^{\gamma}$ and are dominated by the limited data statistics.

By varying independently the requirements on photon and b-jet identification criteria from very loose to very tight selections, we find no evidence of a correlation between the measured photon purity and the 2 b-jet fraction. The obtained photon purity and 2 b-jet fractions are found to be consistent within uncertainties with the values determined using photon and b-jet identification criteria used with the default selections.

The estimated numbers of signal events in each $p_T^{\gamma}$ bin are corrected for the geometric and kinematic acceptance of the photon and jets. The combined acceptance for photon and jets are calculated using SHERPA MC events. The acceptance is calculated for the photons satisfying $p_T^{\gamma} > 30$ GeV, $|\gamma_T| < 1.0$ at particle level. The particle level includes all stable particles as defined in Ref. [23]. The jets are required to have $p_T^{\text{jet}} > 15$ GeV and $|\gamma_T^{\text{jet}}| < 1.5$. As in Refs. [3,6], in the acceptance calculations, the photon is required to be isolated by $E_T^{\mathrm{iso}} = E_T^{\mathrm{jet}}(0.4) - E_T^{\gamma} < 2.5$ GeV, where $E_T^{\gamma}(0.4)$...
is the total transverse energy of particles within a cone of radius $R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4$ centered on the photon direction and $E_T^\gamma$ is the photon transverse energy. The sum of transverse energy in the cone includes all stable particles [23]. The acceptance is driven by selection requirements in $|\eta_{calo}|$ (applied to avoid edge effects in the calorimeter regions used for the measurement) and $|\phi_{calo}|$ (to avoid periodic calorimeter module boundaries), photon $|\eta^\gamma|$ and $p_T^\gamma$, and bin-to-bin migration effects due to the finite energy resolution of the EM calorimeter. The combined photon and jets acceptance with respect to the $p_T$ and rapidity selections varies between 66% and 77% in different $p_T$ bins. Uncertainties on the acceptance due to the jet energy scale [24], jet energy resolution, and the difference between results obtained with SHERPA and PYTHIA are in the range of (8–12)%.

The data, corrected for photon and jet acceptance, reconstruction efficiencies and the admixture of background events, are presented at the particle level by unfolding for effects of detector resolution, photon and $b$-jet detection inefficiencies. The differential cross sections of $\gamma + 2$ $b$-jet production are extracted in five bins of $p_T^\gamma$. They are given in Table 1. 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 [25].

The cross sections fall by more than two orders of magnitude in the range $30 < p_T^\gamma < 200$ GeV. The statistical uncertainty on the results ranges from 4.3% in the first $p_T^\gamma$ bin to 9% in the last $p_T^\gamma$ bin, while the total systematic uncertainty ranges up to 20%. Main sources of systematic uncertainty are the photon purity (up to 8%), photon and two $b$-jet acceptance (up to 14%), $b$-jet fraction (up to 13%), and integrated luminosity (6%) [10]. At higher $p_T^\gamma$, the uncertainty is dominated by the fractions of $b$-jet events and their selection efficiencies.

NLO perturbative QCD predictions, with the renormalization scale $\mu_R$, factorization scale $\mu_F$, and fragmentation scale $\mu_f$ all set to $p_T^\gamma$, are also given in Table 1. The uncertainty from the scale choice is (15–20)% and is estimated through a simultaneous variation of all three scales by a factor of two, i.e., for $\mu_R, \mu_F, \mu_f = 0.5p_T^\gamma$ and $2p_T^\gamma$. The predictions utilize CT10nlo_nf4 PDFs [26] and are corrected for non-perturbative effects of parton-to-hadron fragmentation and multiple parton interactions. The latter are evaluated using SHERPA and PYTHIA MC samples with their standard settings [17,18]. The overall correction varies from about 0.90 at $30 < p_T^\gamma < 40$ GeV to about 0.95 at high $p_T^\gamma$, and an uncertainty of 2% is assigned to account for differences between the two MC generators. NLO predictions on MSTW2008 [27] are close to those made with NNPDF2.3 [28] and are slightly higher (up to 7% at small $p_T^\gamma$) than the predictions using CT10.

The predictions based on the $k_T$-factorization approach [29,30] and unintegrated parton distributions [31] are also given in Table 1. The $k_T$-factorization formalism contains additional contributions to the cross sections due to resummation of gluon radiation diagrams with $k_T^2$ above a scale $\mu^2$ of $O(1)$ GeV, where $k_T$ denotes the transverse momentum of the radiated gluon. Apart from this resummation, the non-vanishing transverse momentum distribution of the colliding partons are taken into account. These effects lead to a broadening of the photon transverse momentum distribution in this approach [29]. The scale uncertainties on these predictions vary from about 31% at $30 < p_T^\gamma < 40$ GeV to about 50% in the highest $p_T^\gamma$ bin.

Table 1 also contains predictions from the PYTHIA [18] MC event generator with the cteg6.1L.pdf set. It includes only 2 → 2 matrix elements (ME) with $gb \rightarrow gb$ and $qg \rightarrow \gamma g$ scatterings (defined at LO) and with $g \rightarrow bb$ splitting in the parton shower (PS). We also provide predictions of the SHERPA MC event generator [17] with the cteg6.6M.pdf set [32]. For $\gamma + b$ production, SHERPA includes all the MEs with one photon and up to three jets, with at least one $b$-jet in our kinematic region. In particular, it accounts for an additional hard jet that accompanies the photon associated with 2 $b$ jets. Compared to an NLO calculation, there is an additional benefit of imposing resummation (further emissions) through the consistent combination with the PS. Matching between the ME partons and the PS jets follows the prescription given in Ref. [33]. Systematic uncertainties are estimated by varying the ME-PS matching.
scale by ±5 GeV around the chosen central value.\textsuperscript{15} As a result, the SHERPA cross sections vary up to ±7%, the uncertainty being largest in the first $p_T$ bin.

All the theoretical predictions are obtained including the isolation requirement on the photon $E_T^{iso} < 2.5$ GeV. The predictions are compared to data in Fig. 4 as a function of $p_T$. The ratios of data to the NLO QCD calculations with CT10 and of different QCD predictions or MC simulation to the same NLO QCD calculations are shown in Fig. 5 as a function of $p_T$.

The measured cross sections are well described by the NLO QCD calculations and the predictions from the $k_T$-factorization approach in the full studied $p_T$ region considering the experimental and theoretical uncertainties. Both of these predictions show consistent behavior, although the predictions from the $k_T$-factorization approach suffer from larger uncertainties. PYTHIA predicts significantly lower production rates and a more steeply falling $p_T$ distribution than observed in data. SHERPA performs better in describing the normalization at high $p_T$, but underestimates production rates compared to that observed in data at low $p_T$.

In addition to measuring the $\gamma + b$-jet cross sections, we also obtain results for the inclusive $\gamma + b$-jet cross section in the same $p_T$ bins. Here we follow the same procedure as described in the previous similar D0 measurement \cite{3}. However, as for the $\gamma + b$-jet cross section measurement, we now use the most recent HF tagging algorithm \cite{13}. The measured cross sections are shown in Fig. 6, and are compared to various predictions in Fig. 7. Data and predictions are also presented in Table 2. The values of the obtained $\gamma + b$-jet cross section are consistent with our previously published results \cite{3}.

We use $\sigma(\gamma + 2\ b$-jet) and $\sigma(\gamma + b$-jet) cross sections to calculate their ratio in bins of $p_T$. Fig. 8 shows the $p_T$ spectrum of the measured ratio. The systematic uncertainties on the ratio vary within (11–15)%, being largest at high $p_T$. The major sources of systematic uncertainties are attributed to the jet acceptance and the estimation of $b$-jet and $2\ b$-jet fractions obtained from the template fits to the data. Fig. 8 also shows comparisons with various predictions. The measurements are well described by the calculations done by NLO QCD and $k_T$-factorization predictions taking into account the experimental and theoretical uncertainties. The scale uncertainties on the NLO calculations are typically < 15%, while they vary up to 35% at high $p_T$ for the $k_T$-factorization approach. The predictions from SHERPA describe the shape, but underestimate the ratio for most of the $p_T$ bins.

\textsuperscript{15} We choose the following ME-PS matching parameters: the energy scale $Q_0 = 15$ GeV and the spatial scale $D = 0.4$, where $D$ is taken to be of the radius of the photon isolation cone.
The differential $\gamma + 2$-jet production cross sections $d\sigma / dp_T^\gamma$ in bins of $p_T^\gamma$ for $|y_T^\gamma| < 1.0$, $p_T^{\text{jett}} > 15$ GeV and $|y^{\text{jett}}| < 1.5$ together with statistical uncertainties ($\delta_{\text{stat}}$), total systematic uncertainties ($\delta_{\text{syst}}$) and total uncertainties ($\delta_{\text{tot}}$) which are obtained by adding $\delta_{\text{stat}}$ and $\delta_{\text{syst}}$ in quadrature. The last four columns show theoretical predictions obtained with NLO QCD, $k_T$-factorization, and with the PYTHIA and the SHERPA event generators.

<table>
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<th>$p_T^\gamma$ bin (GeV)</th>
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<th>$d\sigma / dp_T^\gamma$ (pb/GeV)</th>
<th>Data</th>
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<th>$\delta_{\text{syst}}$ (%)</th>
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The differential $\gamma + 2$-jet production cross sections $d\sigma / dp_T^\gamma$ in bins of $p_T^\gamma$ for $|y_T^\gamma| < 1.0$, $p_T^{\text{jett}} > 15$ GeV and $|y^{\text{jett}}| < 1.5$ together with statistical uncertainties ($\delta_{\text{stat}}$), total systematic uncertainties ($\delta_{\text{syst}}$), and total uncertainties ($\delta_{\text{tot}}$) that are obtained by adding $\delta_{\text{stat}}$ and $\delta_{\text{syst}}$ in quadrature. The last four columns show theoretical predictions obtained with NLO QCD, $k_T$-factorization, and with the PYTHIA and the SHERPA event generators.

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The ratio of differential $\sigma(\gamma + 2 + \text{jet})/\sigma(\gamma + 2 \text{-jet})$ in the same $p_T^\gamma$ range. The ratio agrees with the predictions from NLO QCD and $k_T$-factorization approach within the theoretical and experimental uncertainties in the full studied $p_T^\gamma$ range. These results can be used to further tune theory, MC event generators and improve the description of background processes in studies of the Higgs boson and searches for new phenomena beyond the Standard Model at the Tevatron and the LHC in final states involving the production of vector bosons in association with two $b$-quark jets.

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