Measurement of the differential $\gamma + 2 \text{ b-jet}$ cross section and the ratio 
$\sigma(\gamma + 2 \text{ b-jets})/\sigma(\gamma + \text{ b-jet})$ in pp collisions at $\sqrt{s} = 1.96$ TeV
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We present the first measurements of the differential cross section \( d\sigma/dp_T^\gamma \) for the production of an isolated photon in association with at least two \( b \)-quark jets. The measurements consider photons with rapidities \( |y| < 1.0 \) and transverse momenta \( 30 < p_T < 200 \text{ GeV} \). The \( b \)-quark jets are required to have \( p_T^{b} > 15 \text{ GeV} \) and \( |y^{b}| < 1.5 \). The ratio of differential production cross sections for \( \gamma + 2 \text{-jet} \) to \( \gamma + \text{-jet} \) as a function of \( p_T^\gamma \) is also presented. The results are based on the proton-antiproton collision data at \( \sqrt{s} = 1.96 \text{ TeV} \) collected with the D0 detector at the Fermilab Tevatron Collider. The measured cross sections and their ratios are compared to the next-to-leading order perturbative QCD calculations as well as predictions based on the \( k_T \)-factorization approach and those from the Sherpa and Pythia Monte Carlo event generators.

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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 \( pp \) collisions, \( \gamma + \text{-jet} \) events are produced primarily through the Compton process \( gb \rightarrow \gamma b \), which dominates for low and moderate photon transverse momenta \( (p_T^\gamma) \), and through quark-antiquark annihilation followed by \( gb \rightarrow \gamma b \) and \( gg \rightarrow \gamma b \) scattering [4]. The \( \gamma + \text{-jet} \) process is a crucial component of background in measurements of, for example, \( t\bar{t}\gamma \) coupling [2] and in some searches for new phenomena. A series of measurements involving \( \gamma \) and \( b(\bar{c}) \)-quark final states have previously been performed by the D0 and CDF Collaborations [3, 4].

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 \( \gamma + 2 \text{-jet} \) 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 \( \gamma + 2 \text{-jet} \) 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 \( pp \) collisions. The results
are based on data corresponding to an integrated luminosity of $8.7 \pm 0.5 \text{ fb}^{-1}$ collected with the D0 detector from June 2006 to September 2011 at the Fermilab Tevatron Collider at $\sqrt{s} = 1.96 \text{ TeV}$. The large data sample and use of advanced photon and $b$-jet identification tools 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 $30 < p_T^\gamma < 200 \text{ GeV}$, while the $b$ jets are required to have $p_T^{jet} > 15 \text{ GeV}$ and $|y^{jet}| < 1.5$. 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 $|\eta_{det}| < 1.1$ [15], and two end calorimeters (EC) extending coverage to $|\eta_{det}| \approx 4.2$, 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 (EM$i$, $i = 1 - 4$), with transverse segmentation into cells of size $\Delta \eta_{det} \times \Delta \phi_{det} = 0.1 \times 0.1$ [15], 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 [16] simulation of the D0 detector response. These corrections are $\approx 2\%$ for photon candidates of $p_T^\gamma = 30 \text{ GeV}$, and smaller for higher $p_T^\gamma$.

The data used in this analysis satisfy D0 experiment data quality requirements and are 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 $p_T^\gamma = 30 \text{ GeV}$ and $100\%$ for $p_T^\gamma \gtrsim 40 \text{ GeV}$. Offline event selection requires a reconstructed $pp$ interaction vertex [17] 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 $0.7p_T^\gamma$ to suppress background from $W \rightarrow e\nu$ decays. Such a requirement is highly efficient ($\gtrsim 98\%$) for signal events.

The photon selection criteria in the current measurement are identical to those used in Refs. [2, 3]. The photon selection efficiency and acceptance are calculated using samples of $\gamma + b$-jet events, generated with the SHERPA [18] and PYTHIA [19] Monte Carlo (MC) event generators. The samples are processed through a GEANT-based [16] simulation of the D0 detector. Simulated events are overlaid with data events from random $pp$ crossings to properly model the effects of multiple $pp$ 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 $\approx (71 - 82)\%$ with relative systematic uncertainty of 3%.

For the $\gamma + n \ b$ measurement ($n = 1, 2$), $n$ jets with the highest $p_T$ that satisfy $p_T^{jet} > 15 \text{ GeV}$ and $|y^{jet}| < 1.5$ are selected. Jets are reconstructed using the D0 Run II algorithm [20] 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 $p_T > 0.5 \text{ GeV}$ and at least one hit in the SMT, one of these tracks must also have $|\eta^{jet}| < 2\%$. 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$\text{bl}$ [13]. This algorithm utilizes the longer lifetimes of HF hadrons relative to their lighter counterparts. The MVA$\text{bl}$ 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$\text{bl} > 0.3$ 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, 3,816 $\gamma + 2$ $b$-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 $\gamma + \text{jet}$ 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 [21]. This uncertainty is estimated by varying the production rate of $\pi^{0}$ and $\eta$ mesons by $\pm 50\%$ with respect to their central values [22], and found to be about 6% at $p_{T}^{\gamma} \approx 30 \text{ GeV}$, and $\leq 1\%$ at $p_{T}^{\gamma} \gtrsim 70 \text{ GeV}$.

The fraction of different flavor jets in the selected data sample is extracted using a discriminant, $D_{MJL}$, with distributions dependent on the jet flavors. It combines two discriminating variables associated with the jet, mass of any secondary vertex associated with the jet $M_{SV}$ and the probability for the jet tracks located within the jet cone to come from the primary $p\bar{p}$ interaction vertex. The latter probability is found using the jet lifetime impact parameter (JLIP) algorithm, and is denoted as $P_{\text{JLIP}}$ [17]. The final $D_{MJL}$ discriminant [23] is defined as $D_{MJL} = 0.5 \times (M_{SV}/5 \text{ GeV} - \ln(P_{\text{JLIP}})/20)$, where $M_{SV}$ and $\ln(P_{\text{JLIP}})$ are normalized by their maximum values obtained from the corresponding distributions in data. The data sample with two HF-tagged jets is fitted to templates 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+HF-jets, and HF+HF-jets) are extracted using a discriminant, $D_{MJL}$, defined as $D_{MJL} = P_{\text{JLIP}} - \ln(P_{\text{JLIP}})/20$, where $P_{\text{JLIP}}$ is the probability for the jet tracks located within the jet cone to come from the primary $p\bar{p}$ interaction vertex.
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 uncertainties on the acceptance due to the finite energy resolution of the EM calorimeter. The combined acceptance of the photon and jets. The combined acceptance for photon and jets are calculated using SHERPA MC events. The acceptance is driven by selection requirements in \(|η_{\text{det}}|\) (applied to avoid edge effects in the calorimeter regions used for the measurement) and \(|φ_{\text{det}}|\) (to avoid periodic calorimeter module boundaries), photon \(|γ|\) and \(p_T\), 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 \(c_t\), 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 I. 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 [20].

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 I. 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 cteq6.6M PDFs [27] 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 [13, 19]. 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 $\lesssim$ 2% is assigned to account for differences between the two MC generators.

The predictions based on the $k_T$-factorization approach [28, 22] and unintegrated parton distributions [30] are also given in Table I. 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 $\mathcal{O}(1 \text{ GeV})$, 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 [28].

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 I also contains predictions from the PYTHIA [19] MC event generator with the cteq6.1L PDF set. It includes only $2 \rightarrow 2$ matrix elements (ME) with $gb \rightarrow \gamma b$ and $q\bar{q} \rightarrow \gamma g$ scatterings (defined at LO) and with $q \rightarrow b\bar{b}$ splitting in the parton shower (PS). We also provide predictions of the SHERPA MC event generator [13] with the cteq6.6M PDF set [27]. 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. [31]. Systematic uncertainties are estimated by varying the ME-PS matching scale by ±5 GeV around the chosen central value [22]. As a result, the SHERPA cross sections vary up to ±7%, the uncertainty being largest in the first $p_T^\gamma$ 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 $p_T^\gamma$. The ratios of data to the NLO QCD calculations and of different QCD predictions or MC simulation to the same NLO QCD calculations are shown in Fig. 5 as a function of $p_T^\gamma$.

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 $p_T^\gamma$ 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
which are obtained by adding \( \delta_{NLO \text{ QCD}} \), \( \gamma \), \( \sigma \) to the NLO calculations with predictions from event generators. The uncertainties on the data include both 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 I:** The differential \( \gamma + b \)-jet production cross sections \( \sigma / dp_T^\gamma \) in bins of \( p_T^\gamma \) for \( |y^\gamma| < 1.0 \), \( p_T^{\text{jet}} > 15 \text{ GeV} \) and \( |y^{\text{jet}}| < 1.5 \) 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.

| \( p_T^\gamma \) bin (GeV) | \( \langle p_T^\gamma \rangle \) (GeV) | Data \( \delta_{\text{stat}}(\%) \) | \( \delta_{\text{syst}}(\%) \) | \( \delta_{\text{tot}}(\%) \) | \( \sigma / dp_T^\gamma \) (pb/(GeV)) | NLO | \( k_T \) fact. | PYTHIA | SHERPA |
|--------------------------|-------------------------------|-----------------|-----------------|-----------------|--------------------------|------|-----------|--------|--------|
| 30 – 40                  | 34.5                          | 4.3 +19/−17     | 19/−18          | 2.39×10^{-4}    | 2.20×10^{-4}          | 9.86×10^{-2} | 1.23×10^{-1} |        |        |
| 40 – 50                  | 44.6                          | 5.4 +18/−15     | 19/−16          | 1.68×10^{-4}    | 9.96×10^{-2}          | 4.99×10^{-2} | 6.79×10^{-2} |        |        |
| 50 – 65                  | 56.6                          | 6.2 +15/−14     | 16/−16          | 4.51×10^{-2}    | 4.31×10^{-2}          | 1.99×10^{-2} | 3.29×10^{-2} |        |        |
| 65 – 90                  | 75.2                          | 7.2 +14/−14     | 16/−16          | 1.49×10^{-2}    | 1.48×10^{-2}          | 5.57×10^{-3} | 1.19×10^{-2} |        |        |
| 90 – 200                 | 118.3                         | 9.1 +19/−18     | 21/−21          | 1.67×10^{-3}    | 1.96×10^{-3}          | 5.12×10^{-4} | 1.45×10^{-3} |        |        |

**Table II:** The differential \( \gamma + b \)-jet production cross sections \( \sigma / dp_T^\gamma \) in bins of \( p_T^\gamma \) for \( |y^\gamma| < 1.0 \), \( p_T^{\text{jet}} > 15 \text{ GeV} \) and \( |y^{\text{jet}}| < 1.5 \) 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.

| \( p_T^\gamma \) bin (GeV) | \( \langle p_T^\gamma \rangle \) (GeV) | Data \( \delta_{\text{stat}}(\%) \) | \( \delta_{\text{syst}}(\%) \) | \( \delta_{\text{tot}}(\%) \) | \( \sigma / dp_T^\gamma \) (pb/(GeV)) | NLO | \( k_T \) fact. | PYTHIA | SHERPA |
|--------------------------|-------------------------------|-----------------|-----------------|-----------------|--------------------------|------|-----------|--------|--------|
| 30 – 40                  | 34.5                          | 2.3             | 12              | 1               | 1.52                     | 1.69 | 1.23      |        |        |
| 40 – 50                  | 44.6                          | 2.4             | 11              | 12              | 5.06×10^{-1}          | 5.70×10^{-1} | 4.23×10^{-1} | 5.65×10^{-1} |        |
| 50 – 65                  | 56.6                          | 2.8             | 9               | 10              | 1.75×10^{-1}          | 1.98×10^{-1} | 1.63×10^{-1} | 2.02×10^{-1} |        |
| 65 – 90                  | 75.2                          | 3.3             | 9               | 9               | 4.93×10^{-2}          | 5.43×10^{-2} | 4.27×10^{-2} | 5.41×10^{-2} |        |
| 90 – 200                 | 118.3                         | 3.3             | 13              | 13              | 4.83×10^{-3}          | 5.68×10^{-3} | 3.76×10^{-3} | 5.05×10^{-3} |        |

In addition to measuring the \( \gamma + 2 \)-jet cross sections, we also obtain results for the inclusive \( \gamma + b \)-jet cross section in the same \( p_T^\gamma \) bins. Here we follow the same procedure as described in the previous similar D0 measurement \([3] \). However, as for the \( \gamma + 2 \)-jet cross section measurement, we now use the most recent HF tagging algorithm \([13] \). The measured cross sections are shown in Fig. [8] and are compared to various predictions in Fig. [9]. Data and predictions are also presented in Table III. The values of the obtained \( \gamma + b \)-jet cross section are consistent with our previously published results \([8] \).

We use \( \sigma(\gamma + 2 \text{-jet}) \) and \( \sigma(\gamma + b \text{-jet}) \) cross sections to calculate their ratio in bins of \( p_T^\gamma \). Figure [8] shows the \( p_T^\gamma \) spectrum of the measured ratio. The systematic uncertainties on the ratio vary within \((11-15\%)\), being largest at high \( p_T^\gamma \). The major sources of systematic uncertainties are attributed to the jet acceptances and the estimation of \( b \)-jet and 2 \( b \)-jet fractions obtained from the template fits to the data. Figure [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 \( \lesssim 15\% \), while they vary up to 35\% at high \( p_T^\gamma \) for the \( k_T \)-factorization approach. The predictions from SHERPA fall below the \( p_T^\gamma \) distribution than observed in data. SHERPA performs better in describing the normalization at high \( p_T^\gamma \), but underestimates production rates compared to that observed in data at low \( p_T^\gamma \).

![Graph](data/nlo.png) **Fig. 7:** (Color online) The ratio of \( \gamma + b \)-jet production cross sections to NLO predictions for data and theoretical predictions. The uncertainties on the data include both statistical (inner error bar) and total uncertainties (full error bar). The ratios to the NLO calculations with predictions from SHERPA \([18] \), PYTHIA \([17] \) and \( k_T \)-factorization \([25, 26] \) are also presented along with the scale uncertainties on NLO and \( k_T \)-factorization predictions.
describe the shape, but underestimate the ratio for most of the $p_T^\gamma$ bins. The Pythia model does not perform well in describing the shape and underestimates ratios across all the bins. Experimental results as well as theoretical predictions for the ratios are presented in Table III.

In summary, we have presented the first measurement of the differential cross section of inclusive production of a photon in association with two $b$-quark jets as a function of $p_T^\gamma$ at the Fermilab Tevatron $p\bar{p}$ Collider. The results cover the kinematic range $30 < p_T^\gamma < 200$ GeV, $|y^\gamma| < 1.0$, $p_T^{jet} > 15$ GeV, and $|y^{jet}| < 1.5$. The measured cross sections are in agreement with the NLO QCD calculations and predictions from the $k_T$-factorization approach. We have also measured the ratio of differential $\sigma(\gamma + 2\text{-}b\text{-jet})/\sigma(\gamma + b\text{-jet})$ 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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![FIG. 8: (Color online) The ratio of measured cross sections for $\gamma + 2$ b-jet to $\gamma + b$-jet production as a function of $p_T^\gamma$ compared to theoretical predictions. The uncertainties on the data points include both statistical (inner error bar) and the full uncertainties (full error bar). The measurements are compared to the NLO QCD calculations \[4\]. The predictions from Sherpa \[18\], Pythia \[14\] and $k_T$-factorization \[28, 29\] are also shown along with the scale uncertainties on NLO and $k_T$-factorization predictions.]

TABLE III: The $\sigma(\gamma + 2\text{-}b\text{-jet})/\sigma(\gamma + b\text{-jet})$ cross section ratio in bins of $p_T^\gamma$ for $|y^\gamma| < 1.0$, $p_T^{\text{jet}} > 15$ GeV and $|y^{\text{jet}}| < 1.5$ 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.

| $p_T^\gamma$ bin | $(p_T^\gamma)$ | $\sigma(\gamma + 2\ b\text{-jet})/\sigma(\gamma + b\text{-jet})$ | $\delta_{\text{stat}}$ (%) | $\delta_{\text{syst}}$ (%) | $\delta_{\text{tot}}$ (%) | NLO $k_T$ fact. | PYTHIA | SHERPA |
|------------------|-----------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------|-----------------|-----------------|
|                  | (GeV)           |                             |                             |                             |                             | $k_T$ fact. | $p_T^{\text{jet}}$ | $p_T^{\text{jet}}$ |
| 30 – 40          | 34.5            | 1.48$x10^{-1}$              | 2.3                         | +14/−6                      | 1.58$x10^{-1}$              | 1.42$x10^{-1}$ | 7.25$x10^{-2}$ | 8.42$x10^{-2}$ |
| 40 – 50          | 44.6            | 1.68$x10^{-1}$              | 2.5                         | +13/−7                      | 2.04$x10^{-1}$              | 1.89$x10^{-1}$ | 1.18$x10^{-1}$ | 1.20$x10^{-1}$ |
| 50 – 65          | 56.6            | 2.36$x10^{-1}$              | 2.8                         | +12/−8                      | 2.59$x10^{-1}$              | 2.34$x10^{-1}$ | 1.22$x10^{-1}$ | 1.63$x10^{-1}$ |
| 65 – 90          | 75.2            | 2.54$x10^{-1}$              | 3.3                         | +11/−10                     | 3.05$x10^{-1}$              | 2.92$x10^{-1}$ | 1.30$x10^{-1}$ | 2.20$x10^{-1}$ |
| 90 – 200         | 118.3           | 3.14$x10^{-1}$              | 3.4                         | +15/−15                     | 3.52$x10^{-1}$              | 3.67$x10^{-1}$ | 1.36$x10^{-1}$ | 2.87$x10^{-1}$ |

[1] J. F. Owens, Rev. Mod. Phys. 59, 465 (1987).
[2] T. Stavreva and J. F. Owens, Phys. Rev. D 79, 054017 (2009).
[3] V. M. Abazov et al. (D0 Collaboration), Phys. Lett. B 714, 32 (2012).
[4] H. B. Hartanto and L. Reina, Phys. Rev. D 89, 074001 (2014).
[5] U. Baur, A. Juste, L. Orr, and D. Rainwater, Phys. Rev. D 71, 054013 (2005).
[6] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 102, 192002 (2009).
[7] V. M. Abazov et al. (D0 Collaboration), Phys. Lett. B 719, 354 (2013).
[8] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D 81, 052006 (2010).
[9] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 111, 042003 (2013).
[10] T. Andeen et al., FERMILAB-TM-2365 (2007).
[11] V. M. Abazov et al. (D0 Collaboration), Nucl. Instrum. Methods Phys. Res. A 750, 78 (2014).
[12] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 102, 231801 (2009).
[13] V. M. Abazov et al. (D0 Collaboration), arXiv:1312.7623 (submitted to Nucl. Instrum. Methods Phys. Res. A).
[14] V. M. Abazov et al. (D0 Collaboration), Nucl. Instrum. Methods Phys. Res. A 565, 463 (2006); R. Angstadt et al., Nucl. Instrum. Methods Phys. Res. A 622, 298 (2010); M. Abolins et al., Nucl. Instrum. Methods Phys. Res. A 584, 75 (2008).
[15] 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 $\eta = -\ln\left[\tan(\theta/2)\right]$. Also, $\eta_{\text{det}}$ and $\phi_{\text{det}}$ are the pseudorapidity and the azimuthal angle measured with respect to the center of the detector.
[16] R. Brun and F. Carminati, CERN Program Library Long Writeup, W5013, (1993); we use GEANT version v3.21.
[17] V. M. Abazov et al. (D0 Collaboration), Nucl. Instrum. Methods Phys. Res. A 620, 490 (2010).
[18] T. Gleisberg et al., J. High Energy Phys. 02, 007 (2009). We use SHERPA version v1.3.1.
[19] T. Sjöstrand, S. Mrenna, and P. Z. Skands, J. High Energy Phys. 05, 026 (2006). We use PYTHIA version v6.420 with tune 4C.
[20] G. C. Blazey et al., arXiv:hep-ex/0005012 (2000).
[21] V. M. Abazov et al. (D0 Collaboration), Phys. Lett. B 639, 151 (2006).
[22] T. Binoth et al., Eur. Phys. J. C 4, 7 (2002).
[23] V. M. Abazov et al. (D0 Collaboration), Phys. Lett. B 718, 1314 (2013).
[24] C. Buttler et al., arXiv:0803.0678 [hep-ph], section 9.
[25] V. M. Abazov et al. (D0 Collaboration), arXiv:1312.6873 (accepted by Nucl. Instrum. Methods).
[26] G. D. Lafferty and T. R. Wyatt, Nucl. Instrum. Methods Phys. Res. A 355, 541 (1995).
[27] W. K. Tung et al., J. High Energy Phys. 02, 052 (2007).
[28] A. V. Lipatov and N. P. Zotov, J. Phys. G 34, 219 (2007); S. P. Baranov, A. V. Lipatov, and N. P. Zotov, Eur. Phys. J. C 56, 371 (2008).
[29] A. V. Lipatov and N. P. Zotov, paper in preparation.
[30] M. A. Kimber, A. D. Martin, and M. G. Ryskin, Phys. Rev. D 63, 114027 (2001).
[31] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, Eur. Phys. J. C 63, 189 (2009).
[32] 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.