Photon+jets measurements at D0

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In this paper, we present a few measurements done at the D0 experiment at the Fermilab Tevatron Collider. These measurements include the triple differential cross sections \(d^3\sigma/dp_T^2dy/dy^{\text{jet}}\) of the photon and associated jet production, the photon and heavy flavour \(b\) and \(c\) jet, and finally, study of the event with double parton scattering using \(\gamma+3\) jet events. Each section below presents a brief description of those measurements and results.

I. MEASUREMENT OF THE DIFFERENTIAL CROSS SECTION FOR THE PRODUCTION OF AN ISOLATED PHOTON WITH ASSOCIATED JET IN \(p\bar{p}\) COLLISIONS AT \(\sqrt{s}=1.96\) TeV

The production of a photon with associated jets in the final state is a powerful probe of the dynamics of hard QCD interactions \([1]\). Different angular configurations between the photon and the jets can be used to extend inclusive photon production measurements and simultaneously test the underlying dynamics of QCD hard-scattering subprocesses in different regions of parton momentum fraction \(x\) and large hard-scattering scales \(Q^2\).

Here we present an analysis of photon plus jets production in \(p\bar{p}\) collisions at a center-of-mass energy \(\sqrt{s}=1.96\) TeV in which the most-energetic (leading in \(pt\)) photon is produced centrally with a rapidity \(|y^\gamma|<1.0\) \([2]\). The cross section as a function of photon transverse momentum \(p_T^\gamma\) is measured differentially for four separate angular configurations of the highest \(p_T\) (leading) jet and the leading photon rapidities. The leading jet is required to be in either the central \((|y^{\text{jet}}|<0.8)\) or forward \((1.5<|y^{\text{jet}}|<2.5)\) rapidity intervals, with \(p_T^{\text{jet}} > 15\) GeV. The four angular configurations studied are: central jets with \(y^\gamma\cdot y^{\text{jet}}>0\) and with \(y^\gamma\cdot y^{\text{jet}}<0\), and forward jets with \(y^\gamma\cdot y^{\text{jet}}>0\) and with \(y^\gamma\cdot y^{\text{jet}}<0\). The total \(x\) and \(Q^2\) region covered by the measurement is 0.007 \(\lesssim x \lesssim 0.8\) and 900 \(\lesssim Q^2 \lesssim 400\) GeV\(^2\), extending the kinematic reach of previous photon plus jet measurements (see refs. inside \([2]\)). Ratios between the differential cross sections in the four studied angular configurations are also presented. The measurements are compared to the corresponding theoretical predictions.

The data presented here correspond to an integrated luminosity of 1.01 \(\pm\) 0.06 fb\(^{-1}\) collected using the D0 detector \([3]\) at the Fermilab Tevatron \(p\bar{p}\) collider operating at a center-of-mass energy \(\sqrt{s}=1.96\) TeV.

Events containing at least one hadronic jet are selected. Jets are reconstructed using the D0 Run II jet-finding algorithm with a cone of radius 0.7 \([4]\), and are required to satisfy quality criteria which suppress background from leptons, photons, and detector noise effects. Jet energies are corrected to the particle level.

In total, about 1.4 million candidate events are selected after application of all selection criteria. A correction for the \(\{\gamma+jet\}\) event purity \(P\) is then applied to account for the remaining background in the region \(Q_{Njet}>0.7\). The distribution of the ANN output for the simulated photon signal and dijet background samples are fitted to the data for each \(p_T^{\gamma}\) bin using a maximum likelihood fit \([5]\) to obtain the fractions of signal and background components. The found purities vary as 0.52 − 0.99 for 30 < \(p_T^{\gamma}\) < 400 GeV.

The data are compared to next-to-leading order (NLO) QCD predictions obtained using JETPHOX \([7]\), with CTEQ6.5M PDF \([6]\) and BFG fragmentation functions of partons to photons \([8]\). The renormalization, factorization, and fragmentation scales \((\mu_R, \mu_F, \text{and } \mu_f)\) are set equal to \(p_T^{\gamma}\cdot f(y^\gamma)\), where \(f(y^\gamma) = [(1+\exp(-2|y^\gamma|))/2]^{1/2}\) and \(y^\gamma = 0.5(y^\gamma-y^{\text{jet}})\) \([9]\).

The prediction using the CTEQ6.5M PDF and BFG fragmentation sets does not describe the shape of the cross section over the whole measured range. In particular, the prediction is above the data for events with \(|y^{\text{jet}}|<0.8\) in the region \(p_T^{\gamma}>100\) GeV and below the data for jets produced in the \(1.5<|y^{\text{jet}}|<2.5\) rapidity interval, with \(p_T^{\text{jet}}<50\) GeV. Most of the data points in these \(p_T^{\gamma}\) and rapidity regions are \(\sigma_{\text{tot}}\) outside of the CTEQ6.5M PDF set uncertainty range which is shown by the shaded region in the figure and calculated according to the prescription in \([6]\). Note that the data-to-theory ratios have a shape similar to those observed in the inclusive photon cross sections measured by the UA2 \([10]\), CDF \([11]\) and D0 \([12]\) collaborations.

The experimental systematic uncertainties are reduced further by measuring the ratios between the differential cross sections \(D = d^3\sigma/dp_T^2dy/dy^{\text{jet}}\) in the different regions. Most of the systematic uncertainties related to the identification of central photons then cancel, and only systematic uncertainties related to the \(pp \rightarrow \gamma+jet+X\) event purities and the jet selection efficiency (when measuring ratios between central and forward jet regions) remain. Measured ratios between the differential cross sections in the different regions are presented in Fig.\(2\). The ratios also significantly reduces theoretical scale uncertainties \([2]\). The shapes of the measured ratios between the cross sections in the different regions, in general, are qualita-
Photons produced in association with heavy quarks $Q (\equiv c$ or $b$) in the final state of hadron-hadron interactions provide valuable information about the parton distributions of the initial state hadrons \cite{13, 14}. Such events are produced primarily through the QCD Compton-like scattering process $qQ \rightarrow \gamma Q$ but also through quark-antiquark annihilation $q\bar{q} \rightarrow \gamma g \rightarrow \gamma QQ$. Consequently, $\gamma + X$ production is sensitive to the $b$, $c$, and gluon ($g$) densities within the colliding hadrons, and can provide constraints on parton distribution functions that have substantial uncertainties \cite{6}. The heavy quark and gluon content is an important aspect of QCD dynamics and of the fundamental structure of the proton. In particular, many searches for new physics, e.g. for certain Higgs boson production modes \cite{15, 16, 17}, will benefit from the increased PDF precision with respect to the heavy quark and gluon content of the proton.

This section presents the first measurements of the inclusive differential cross sections $d^3\sigma/(dp_T^2dy^\gamma dy^{\text{jet}})$ for $\gamma + b + X$ and $\gamma + c + X$ production in $p\bar{p}$ collisions, where $y^\gamma$ and $y^{\text{jet}}$ are the photon and jet rapidities \cite{18}. The results are based on an integrated luminosity of $1.02 \pm 0.06$ fb$^{-1}$ collected with the D0 detector at the Fermilab Tevatron Collider at $\sqrt{s} = 1.96$ TeV. The highest $p_T$ (leading) photon and jet are required to have $|y^\gamma| < 1.0$ and $|y^{\text{jet}}| < 0.8$, and transverse momentum $30 < p_T < 150$ GeV and $p_T^{\text{jet}} > 15$ GeV. This selection allows one to probe PDFs in the range of parton-momentum fractions ($x$) $0.01 \lesssim x \lesssim 0.3$, and hard scatter scales of $9 \times 10^2 \lesssim Q^2 \equiv (p_T^\gamma)^2 \lesssim 2 \times 10^3$ GeV$^2$.

Differential cross sections are presented for two regions of kinematics, defined by $y^\gamma$ and $y^{\text{jet}}$, in each measured interval, to the NLO QCD predictions, estimated using JETPHOX, as shown for three different scales: $\mu_{R,F} = \mu_0 = 0.5 \mu_0$, and $2 \mu_0$, where $\mu_0 = p_T^\gamma f(y^\gamma)$.
are reconstructed using the D0 Run II algorithm \cite{4} with a radius of 0.5. Light jets are suppressed using a dedicated artificial neural network (b-ANN) \cite{19} that exploits the longer lifetimes of heavy-flavor hadrons relative to their lighter counterparts. The leading jet is required to have a b-ANN output value $> 0.85$.

About 13,000 events remain in the data sample after applying all selection criteria. To estimate the photon purity, the $\gamma$-ANN distribution in data 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 $p_T^\gamma$ bin, yielding photon purities between 51% and 93% for $30 < p_T^\gamma < 150$ GeV. The fractional contributions of $b$ and $c$ jets are determined by fitting templates of $P^\text{HF-jet} = -\ln \prod_i P^\text{track}_i$ to the data, where $P^\text{track}$ is the probability that a track originates from the primary vertex, based on the significance of the track's distance of closest approach to the primary vertex. Templates are used for the shape information of the $P^\text{HF-jet}$ distributions. For $b$ and $c$ jets these are extracted from MC events while the light jet template is taken from a data sample enriched in light jets, which is corrected for contributions from $b$ and $c$ quarks.

The result of a maximum likelihood fit, normalized to the number of events in data, is shown in Fig.\ref{fig:4} for $50 < p_T^\gamma < 70$ GeV, as an example. The estimated fractions of $b$ and $c$ jets in all $p_T^\gamma$ bins vary between 25–34% and 40–48%, respectively. The corresponding uncertainties range between 7–24%, dominated at higher $p_T^\gamma$ by the limited data statistics.

The measured differential cross sections are shown in Fig.\ref{fig:4} for $\gamma + b + X$ and $\gamma + c + X$ production as a function of $p_T^\gamma$ for the jet and photon rapidity intervals in question. The cross sections fall by more than three orders of magnitude in the range $30 < p_T^\gamma < 150$ GeV. The statistical uncertainty on the results ranges from 2% in the first $p_T^\gamma$ bin to $\approx 9\%$ in the last bin, while the total systematic uncertainty varies between 15% and 28%.

NLO pQCD predictions \cite{20}, with the renormali-
tion scale $\mu_R$, factorization scale $\mu_F$, and fragmentation scale $\mu_f$, all set to $p_T^{\gamma}$, are compared to data in Fig. 4. The ratios of the measured to the predicted cross sections are shown in Fig. 5. The uncertainty from the choice of the scale is estimated through a simultaneous variation of all three scales by a factor of two, i.e., to $\mu_R, \mu_F, \mu_f = 0.5p_T^{\gamma}$ and $2p_T^{\gamma}$. The predictions utilize CT10.6M PDFs [14], and are corrected for effects of parton-to-hadron fragmentation. This correction for $b(c)$ jets varies from 7.5% (3%) at $30 < p_T^{\gamma} < 40$ GeV to 1% at $90 < p_T^{\gamma} < 150$ GeV.

The pQCD prediction agrees with the measured cross sections for $\gamma + b + X$ production over the entire $p_T^{\gamma} < 70$ GeV, and with $\gamma + c + X$ production for $p_T^{\gamma} > 70$ GeV, the measured $\gamma + c + X$ cross section is higher than the prediction by about 1.6–2.2 standard deviations (including only the experimental uncertainties) with the difference increasing with growing $p_T^{\gamma}$.

Parameterizations for two models containing intrinsic-charm (IC) have been included in CT10.6M [14], and their ratios to the standard CT10q predictions are also shown in Fig. 5. Both non-perturbative models predict an increased $\gamma + c + X$ cross section, and for the BHPS model [14] it grows with $p_T^{\gamma}$. The observed difference may also be caused by an underestimated contribution from the $g \rightarrow Q\bar{Q}$ splitting in the annihilation process that dominates for $p_T^{\gamma} > 90$ GeV [21].

### III. Double Parton Interactions in $\gamma + 3$ jet events in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV in DØ

Many features of high energy inelastic hadron collisions depend directly on the parton structure of hadrons which is still not yet well understood at both the theoretical and experimental levels. Phenomenologically, the proton (or antiproton) may be viewed, in the first naive approximation, as an object composed of three light quarks (or anti-quarks). The study of this structure is founded mainly on the use of a simplified theoretical model which considers high energy inelastic scattering of nucleons as a process involving a single collision of one quark or gluon from one nucleon with one quark or gluon from the other nucleon. In this approach, additional “spectator” partons do not take part in the hard $2 \rightarrow 2$ parton collision and form the so-called “underlying event”.

Another, much less developed, approach is based on models in which there might be more than one hard interaction of parton pairs in one collision of nucleons. Since each incoming hadron is a composite object, consisting of many partons, such a probability should be non-zero. Models with multiple parton collisions have been considered in a few theoretical papers (see refs. inside [22]). It is obvious that the rate of events with double parton scattering (DPS) depends on how the partons are distributed within the nucleon. The form of the parton spatial distribution and possible correlations between partons is practically unknown. This information is hard to obtain within the present theoretical models based on perturbative QCD and makes a relevant measurement particularly important.

Recently the information about a fraction of the double parton interactions has become very important due to growing Tevatron luminosity and upcoming LHC experiments. It opens the possibility to search for signals from new physics processes for which the DPS events may give a noticeable background.

So far, there have been only four dedicated measurements studying double parton scattering: the AFS experiment in $pp$ collisions at $\sqrt{s} = 63$ GeV [23], UA2 in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV [24] and two by CDF in $p\bar{p}$ collisions $\sqrt{s} = 1.8$ TeV [25, 26].

In the present analysis, we use a sample of $\gamma + 3$ jets events collected by the D0 experiment during Run IIa at the integrated luminosity of 1 fb$^{-1}$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [22]. We determine the fraction of the double parton interactions in a single $pp$ collision and also the value of “effective cross section” $\sigma_{\text{eff}}$. The latter allows, with the known cross sections $\sigma^{A}$ and $\sigma^{B}$ for two independent parton scatterings A and B, to calculate $\sigma_{\text{DPS}}$ cross section:

$$\sigma_{\text{DPS}} = \frac{\sigma^{A}\sigma^{B}}{\sigma_{\text{eff}}}$$  \hspace{1cm} (1)

Here the normalization factor $\sigma_{\text{eff}}$ is a parameter that can be directly related to the distance between partons in the nucleon. If the partons are uniformly distributed inside the nucleon (large $\sigma_{\text{eff}}$), $\sigma_{\text{DPS}}$ will be rather low and, conversely, it should increase for a highly concentrated parton spatial densities (small $\sigma_{\text{eff}}$). A better energy measurement of photons as compared with jets helps in separating the DP scatterings and allows us to better fix the scale of the main hard interaction.

In the current analysis, to extract $\sigma_{\text{eff}}$ we use a technique that operates only with quantities determined from data analysis and minimizes many theoretical assumptions [22, 26] that were used in some previous measurements. Towards this aim, we measure the number of DP $\gamma + 3$ jets events and the number of $\gamma + 3$ jets events with hard interactions occurring in two separate $p\bar{p}$ collisions. The latter class of events will be called double interactions (DI). Assuming independent (uncorrelated) scatterings in the DP process [27, 28], the DP and DI events should be kinematically identical and differ by just amount of “underlying” energy in one- and two-vertex events. The expression for the effective cross section $\sigma_{\text{eff}}$ can be written in the following form:

$$\sigma_{\text{eff}} = \frac{N_{\text{DI}}}{N_{\text{DPS}}} \frac{N_c(1)}{2N_c(2)} \sigma_{\text{hard}}.$$  \hspace{1cm} (2)
Here $N_{\text{DI(DP)}}$ is the number of DI(DP) events, $N_i(1)$ and $N_i(2)$ are the numbers of beam crossings with 1 and 2 hard collisions, and $\sigma_{\text{hard}}$ is the cross section of the hard $pp$ interaction. We measure $\sigma_{\text{eff}}$ in three bins of the 2nd (ordered in $p_T$) jet ($p_T^{\text{jet2}}$) which serves as a scale of the additional parton-parton interaction.

We used data collected with the D0 detector during Run IIa which corresponds an integrated luminosity of about 1.02 ± 0.06 fb$^{-1}$. The data sets and $\gamma$+jets selection criteria, analogous to the previous $p\bar{p} \rightarrow \gamma + \text{jet} + X$ measurements [22, 18], have been used in this analysis.

The main background for the DP events is caused by the $\gamma + 3$ jets events resulting from the single parton (SP) scatterings with hard gluon radiation in the initial or final state $gg \rightarrow q\bar{q}\gamma gg$ or $q\bar{q} \rightarrow q\bar{q}\gamma gg$. The fraction of the DP events is determined in this analysis using a set of variables sensitive to the kinematic configurations of the two independent scatterings of parton pairs, specifically to the difference between between the $p_T$ imbalances of two pairs in $\gamma + 3$ jets events:

$$S_{p_T} = \frac{1}{\sqrt{2}} \sqrt{\left(\frac{p_T(\gamma, i)}{\delta p_T(\gamma, i)}\right)^2 + \left(\frac{p_T(j, k)}{\delta p_T(j, k)}\right)^2}$$

(3)

Two other variables, similar to [4], have also been used in the analysis [22] for a cross-check. In the equations above, $p_T(\gamma, i)$ and $p_T(j, k)$ are the $p_T$ vectors of the total transverse momenta of the two two-body system, and $\delta p_T(\gamma, i), \delta p_T(j, k)$ are the corresponding uncertainties. The pairs are constructed by grouping $\gamma$ with 3 jets in three possible configurations. The configuration that gives the minimum $S$ is selected for each of the $S$-family variables. In most events $S$ is minimized by pairing the photon with the leading jet, while the additional jets both come from dijet system or one of them is replaced by the radiation jet.

The $\Delta S$-family variables are allied to the $S$-family. They are defined as an azimuthal angle between the $p_T$ vectors of the pairs that give a minimum $S$ value:

$$\Delta S = \Delta \phi \left( p_T^{\gamma,jet_1}, p_T^{\gamma,jet_2} \right)$$

(4)

where $p_T^{\gamma,jet_1}$ and $p_T^{\gamma,jet_2}$ are the total $p_T$ balance vectors of the pairs ($\gamma + jet_1$) and ($jet_2 + jet_3$) which give minimal $S$.

The models for signal DP (and DI) events have been constructed directly from data mixing $\gamma + \geq 1$ jet and dijet minimum bias events in the one- and two- (and two-) vertex data [22]. Then the fractions of DP events have been found from analysis of shapes for $\Delta S$ distributions in the signal events and data in the adjacent $p_T^{\text{jet2}}$ bins for which we should expect different DP fractions [28]. Fractions of DI events have been found fitting the shapes for $\Delta S$ distributions of signal and background events to data. The obtained DP fractions are shown in Tables I while the DI fractions vary as 0.189 ± 0.029 at 15 < $p_T^{\text{jet2}}$ < 20 GeV, 0.137 ± 0.027 at 20 < $p_T^{\text{jet2}}$ < 25 GeV and 0.094 ± 0.025 at 25 < $p_T^{\text{jet2}}$ < 30 GeV.

| $p_T^{\text{jet2}}$ | 15 − 20 | 20 − 25 | 25 − 30 |
|-------------------|---------|---------|---------|
| $f_{\text{DP}}$  | 0.466 ± 0.041 | 0.334 ± 0.023 | 0.235 ± 0.027 |

TABLE I: Fractions of DP events $f_{\text{DP}}$ found for the three $p_T^{\text{jet2}}$ intervals (GeV).

| $p_T^{\text{jet2}}$ | 15 − 20 | 20 − 25 | 25 − 30 |
|-------------------|---------|---------|---------|
| $\sigma_{\text{eff}}$ | 16.2 ± 2.8 | 13.8 ± 3.1 | 11.5 ± 4.7 |

TABLE II: Effective cross section $\sigma_{\text{eff}}$ (mb) found in the three $p_T^{\text{jet2}}$ intervals (GeV).

The resulting values of $\sigma_{\text{eff}}$ with total (systematic + statistics) uncertainties are given in Table II for the three $p_T^{\text{jet2}}$ bins. The total systematic uncertainty varies between 19% and 31% and is mainly caused by the determination of the DI and DP fractions as well as by the ratios of the DP/DI selection efficiencies.

One can see that the obtained $\sigma_{\text{eff}}$ values in different jet $p_T$ bins agree with each other within their uncertainties. Using this fact and also that the uncertainties in different jet $p_T$ bins have very small correlation, we can calculate the $\sigma_{\text{eff}}$ average value over the three jet $p_T$ bins. It gives us

$$\sigma_{\text{aver}} = 15.1 ± 1.9 \text{ mb}.$$ (5)

It is worth mentioning that the obtained average value is in the range of those found in previous analogous measurements [24]–[26]. This closeness may indicate a tendency for a stable behavior of $\sigma_{\text{eff}}$ with respect to the transverse momentum of the jet produced in the second parton-parton interaction.

IV. CONCLUSION

The presented measurements of production cross sections for $\gamma + \text{jet}$, $\gamma + \text{heavy flavour jet}$ and study of the events with double parton scatterings provide precision tests of perturbative QCD as well as information on the fundamental structure of the nucleon; momentum and spatial distributions of partons in the nucleon. In addition to these important aspects of QCD dynamics, this knowledge should be very helpful for many searches for new physics since, for example, $\gamma + \text{jet}$ and $\gamma + b(c)$ jets are noticeable components for the background to many Higgs boson decay modes (e.g. $h \rightarrow \gamma\gamma, bb$) as well to extra dimensions with graviton ($G \rightarrow ee, \gamma\gamma$) and technicolor (e.g. $\omega_T \rightarrow \gamma\pi^0, a_T^\pm \rightarrow \gamma\pi^\pm$ with $\pi^0 \rightarrow bb, \pi^\pm \rightarrow b\bar{c}, b\bar{c}$).

Proceedings of the DPF-2009 Conference, Detroit, MI, July 27-31, 2009
Knowledge of parton matter structure and parton correlations being extremely valuable per se is also important for understanding multijet production characteristic for many physics final states, especially expected in many SUSY models [21].