Study of parton k_T smearing effects in direct photon production at the Fermilab Tevatron

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Previous detailed studies of direct photon production from both fixed-target and collider experiments have witnessed a pattern of deviation between the measured inclusive cross sections and the corresponding theoretical expectations in the low transverse momentum (p_T) regime. Most data sets display steeper p_T dependence than the next-to-leading-order (NLO) perturbative QCD (PQCD) calculations with standard choices of scales and parton distribution functions in this region. A simple implementation of higher-order soft-gluon corrections to the NLO PQCD predictions significantly improves the agreement between data and theory. This interesting feature motivated us to investigate the DØ and CDF measurements of inclusive photon cross section at $\sqrt{s}=1.8$ TeV from the run $1b$ and also at $\sqrt{s}=630$ GeV. We use the latest updated parton distribution function CTEQ6M in the NLO QCD calculations for direct photon cross section to describe the data. The conventional theoretical uncertainties originating from scale dependence and gluon distributions have been illustrated. We estimate the impact of additional soft-gluon radiation on the direct photon production using PYTHIA (LO PQCD), which adds transverse momentum k_T to initial-state partons through a Gaussian smearing. The impact of k_T effects on the discrepancy in the low-p_T region is explored using a phenomenological model, wherein we merge the NLO calculations with k_T correction factors. We show that this approach provides a much more acceptable description of the Fermilab Tevatron data.

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I. INTRODUCTION

The production of direct photons [1–3] with large transverse momenta p_T in hadronic collisions, pp, $\bar{p}p\rightarrow\gamma X$, has long been established as an ideal testing ground for the formalism of perturbative quantum chromodynamics (PQCD) [4]. This is because the pointlike coupling of the photon to the hard interaction, in principle, makes this process ideally free from uncertainties inherent in jet reconstruction (as in the case of jet production) or in fragmentation of partons into hadrons (as in the inclusive hadron production), and hence a clean probe of the hard-scattering dynamics. This process is complementary to the electroweak processes of deep inelastic scattering (DIS) and Drell-Yan (DY) pair production and to pure QCD processes such as inclusive production of jets or heavy flavors. One of the main motivations of direct photon investigation is that its production mechanism offers a valuable opportunity to place strong constraints on the gluon distribution $G(x,Q)$, inside the colliding hadrons in the global analysis of parton distributions [4,5]. The sensitivity to $G(x,Q)$ arises from the dominant contribution of the Compton scattering subprocess $qg\rightarrow q\gamma$ with a gluon in the initial state to direct photon production at leading-order (LO) QCD [1] in all kinematic regions of pp scattering, as well as for low to moderate values of the parton momentum fraction x in $\bar{p}p$ interaction. The gluon distribution is relatively well constrained by DIS and DY data for $x<0.1$, and by collider data on jet production at moderate x (0.1–0.25) [6], but is less constrained at larger x where the direct photon data are particularly important [7]. The potential usefulness of the direct photon cross section necessitates a proper theoretical understanding of the process. However, both the completeness of the current theoretical description of the process at the next-to-leading order (NLO) and the consistency among different experimental data sets have been subjects of intense debate [8,9].

The LO contribution to the direct photon production is given by the Born-level subprocesses $q(\text{or }\bar{q})g\rightarrow\gamma q(\text{or }\bar{q})$ and $q\bar{q}\rightarrow\gamma g$ [1,2]. The computation of the NLO contributions yields $O(\alpha_s^2)$ corrections resulting from the subprocesses $q\bar{q}\rightarrow\gamma gg$, $q(\text{or }\bar{q})g\rightarrow\gamma gq(\text{or }\bar{q})$, and from virtual corrections to the Born-level subprocesses [1,2]. Unfortunately, in experiment, one has to deal with a substantial background of photons from the π^0 decay. In addition, high-p_T photons can be produced in jets, such as a parton resulting from a pure QCD reaction, fragments into a photon, which can also mimic the direct photon signal. Whereas the contribution from the fragmentation or bremsstrahlung photons remains small (at most 20%) at fixed-target energies, it overwhelms the signal at the collider regime [10] particularly at large center-of-mass energies and low p_T. To suppress the background, the experimental selection of direct photons imposes "isolation" cuts on the electromagnetic trigger. Generally, these are of the form of an upper limit on the amount of hadronic transverse energy which can accompany the electromagnetic trigger inside a cone of size $\Delta R=\sqrt{\Delta\eta^2+\Delta\phi^2}$ about the trigger (η and ϕ are the pseudorapidity and the azimuthal angle, respectively). These isolation criteria effectively remove most of the bremsstrahlung contribution from the data sample [11].

The global QCD analysis of the direct photon production process from different experiments over a wide range of $\sqrt{s}$ has revealed a consistent picture of disagreement between the NLO QCD predictions [12–16] and the measured cross section for the transverse momentum (p_T) distribution of the

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photon [9]. Characteristically, in both fixed-target [17–19] and collider experiments [20–25], there is an experimental excess of photons in the low-p_T region. The most serious problems relate to the high-statistics E706 sample, where the NLO theory dramatically underestimates the observed cross sections [19]. At collider energies, there is comparatively less reason for concern, but here also the agreement is not satisfactory. The deviation occurs at different x values for experiments at different energies rather than in any specific x range [9]. Thus global fits with new parton distribution functions (PDFs) cannot be expected to cure this discrepancy. The CERN Intersecting Storage Rings and fixed-target data are also almost insensitive to fragmentation processes, thus it is difficult to derive any conclusion based on fragmentation of quarks. The obvious source of uncertainty due to the choice of QCD scales also cannot be held responsible for the discrepancy, since it provides a small normalization shift with no change in shape. One proposed explanation [9,26–29] is that the present NLO PQCD calculations may not adequately account for a photon-jet system "recoil" or "k_T kick" due to multiple soft-gluon radiation [30] by the initial-state partons prior to the hard scattering.[1] However, when the impact of this k_T is incorporated in the NLO calculations the resulting cross section shows much more compatibility with the observations [26–29].

After a brief overview of partonic transverse momentum (k_T) effects and its application to the theoretical predictions for the direct photon cross section through a phenomenological model, we present a study of the measurements of isolated direct photon cross section by the DØ and the CDF detectors at the Fermilab Tevatron collider at the center-of-mass energy $\sqrt{s}=1.8$ TeV during run 1b and also at $\sqrt{s}=630$ GeV. The measured cross sections are compared with the present NLO PQCD calculations using the latest updated set of PDF, CTEQ6M [31], and the usual choice of scales. Then we zoom in on the existing discrepancies between data and theory at low p_T. Concentrating on the DØ data, we examine the effects of the theoretical uncertainties due to the choice of scales and parton densities on the discrepancy. We investigate the effects of multiple soft-gluon radiation from the initial-state partons associated with direct photon production by simulating events using PYTHIA. LO PQCD has been used to estimate the impact of k_T on the inclusive production of high-p_T direct photons. We then proceed to show that the inclusion of the higher-order effects of soft-gluon emission in the theoretical calculations through a simple implementation of the supplemental k_T smearing provides a reasonably consistent description of the observations.

II. PARTON TRANSVERSE MOTION (k_T)

In the conventional QCD hard-scattering formalism, the interacting partons are treated as if they were collinear with the incoming hadrons and the partons emerging after the hard scattering were produced back to back with equal p_T in a plane perpendicular to the beam axis. However, in the hadron-hadron center-of-mass frame, the colliding partons may have some transverse momentum k_T with respect to each other [32], which will appear as a net p_T imbalance among the outgoing particles in the hard scatter, and is therefore reflected in the vector sum of the individual p_T values of the outgoing particles (Q_T). If, say, in the Compton process $qg\to q\gamma$ the initial partons have a nonzero k_T, the $q\gamma$ pair in the final state will acquire a net transverse momentum Q_T, which will make the process softer than it would be otherwise and result in an enhancement in the photon p_T spectrum [33]. If the outgoing particles are pairs of photons or leptons, then Q_T should provide a good measure of k_T, with the average value of k_T per parton ($\langle k_T\rangle)\approx\langle Q_T\rangle/\sqrt{2}$ [26].

Measurements of dimuon, diphoton, and dijet production have indicated the presence of a significant effective k_T [26], as do the analysis of $\pi^0\pi^0$ and $\gamma\pi^0$ [27]. The comparisons of the p_T spectra for charm-particle hadron production and high-p_T charged-D cross section to the NLO PQCD results have also provided an evidence that substantial k_T may be required to properly describe the data [19]. The values of $\langle k_T\rangle$ suggested by the kinematic distributions of the high-mass pairs range from ~ 1 GeV at fixed-target energies ($\sqrt{s}<40$ GeV), increasing upto ~ 3–4 GeV at the Fermilab Tevatron collider ($\sqrt{s}=1.8$ TeV), the growth being approximately logarithmic with increasing center-of-mass energy [26] (the value expected at the CERN Large Hadron Collider, $\sqrt{s}=14$ TeV, lies in the range of 6.5–7.0 GeV). These values of $\langle k_T\rangle$ cannot be explained by primordial (intrinsic) transverse momentum reflecting the confinement of the partons inside the finite size of the hadron according to the uncertainty principle, which is expected to make a contribution only of the order of 0.3–0.5 GeV. Such a large value is an indication of its perturbative nature. The major part of this effect can, however, be attributed to the multiple soft-gluon emission by the partons prior to the hard scattering which imparts a transverse boost to the produced particles [26,27,29]. Similar effects of k_T can be expected to be present in all hard-scattering processes, particularly in the inclusive production of jets or direct photons [26,27,29].

Present NLO PQCD calculations for direct photon cross section includes at most one extra gluon emission and hence may not adequately account for the transverse motion of interacting partons [29]. Inclusion of these k_T effects in the NLO calculations in explaining the discrepancy at low p_T seems to be an interesting alternative, since any uniform smearing on a steeply falling p_T distribution enhances significantly only the low-p_T end of the spectrum, where the discrepancy between the data and theory is observed to be significant [9]. A detailed overview of the k_T effects and its application to the available direct photon and (π^0) data can be found in Refs. [26–29].

III. TREATMENT OF SOFT-GLUON EFFECTS

In high-p_T hadronic scattering a resummation of high-order perturbative processes is required to incorporate the transverse effects of soft-gluon radiation. This has been

[1]We should add that this view is not universally held, see, for example, Ref. [8].

achieved for some hadronic reactions, such as W/Z, DY, and direct photon pair production, where large-Q^2 parton scattering results in a colorless final state. It is quite challenging to extend these calculations to inclusive direct photon production processes that involve a parton jet in the final state. Sustained efforts are underway to arrive at a fully resummed PQCD description [10,34–38] of soft-gluon emission effects. Two independent threshold-resummed PQCD calculations have been developed [35,36], which do not include k_T effects, but exhibit less dependence on the QCD scales than the NLO theory. A formalism for simultaneous treatment of recoil and threshold corrections in inclusive single-photon cross sections has been developed [10] which shows a good promise for improving the theoretical description of the data, but is presently unavailable for detailed comparisons. This approach accounts explicitly for the recoil from soft radiation in the hard scattering, and conserves both energy and transverse momentum for the resummed radiation. A complete treatment of soft-gluon radiation in high-p_T production should eventually predict the effective k_T values expected for each process and $\sqrt{s}$. The long-standing theoretical complications associated with direct photon cross section have discouraged the CTEQ Collaboration from using the direct photon data in their recent fits [29]. With the advent of more complete theoretical treatments of the soft-gluon effects, the fixed-target direct photon data from E706 should have a great impact on the determination of the gluon behavior at large x.

In order to investigate deviations between data and NLO PQCD calculations for the p_T distribution of direct photons, some *ad hoc* procedures have been used previously, which approximates the radiative corrections. One such approach involves adding the extra multiple parton emission effects to the NLO PQCD via a parton shower model [38]. However, an interesting and more intuitive technique has been the use of a simple phenomenological k_T-smearing model [26,27]. In this approach, the soft-gluon radiation is parametrized in terms of an effective $\langle k_T\rangle$ that provides an additional transverse impulse to the outgoing partons. Since the inclusive spectra fall steeply with increasing p_T, the introduction of transverse motion of initial-state partons prior to the hard scattering can shift the production of final-state particles from lower to higher values of p_T, effectively enhancing the expected yield. This approach has been followed in the present work.

In PQCD, the expression for the LO cross section for direct photon production at large p_T has the form [26]

$$\sigma(h_1h_2\to\gamma X)=\int dx_1dx_2f_{a_1/h_1}(x_1,Q^2)\times f_{a_2/h_2}(x_2,Q^2)\hat{\sigma}(a_1a_2\to\gamma a_3), \quad (1)$$

where $\hat{\sigma}$ is the hard-scattering matrix element, and f_{a_1/h_1} and f_{a_2/h_2} are the PDFs for the colliding partons a_1 and a_2 in hadrons h_1 and h_2, respectively. To introduce transverse kinematics of the initial-state partons, we extend each integral over the PDFs to the k_T space,

$$dx f_{a/h}(x,Q^2)\to dx\, d^2k_T g(k_T) f_{a/h}(x,Q^2),$$

and assume a Gaussian type of k_T distribution, $g(k_T)$ for the partons inside the hadron [1,26], given by

$$g(k_T)=\frac{e^{-k_T^2/\langle k_T^2\rangle}}{\pi\langle k_T^2\rangle}.$$

Here, $\langle k_T^2\rangle$ is the square of the two-dimensional rms width of the k_T distribution for one parton and is related to the square of the average of the absolute value of k_T of one parton, $\langle k_T\rangle$, through

$$\langle k_T^2\rangle=\frac{4\langle k_T\rangle^2}{\pi}.$$

Such a treatment of modified parton kinematics in evaluating the cross sections can be implemented in a Monte Carlo framework. The QCD Monte Carlo event generator PYTHIA [39] simulates the effects of soft-gluon emission in a model implemented in a LO PQCD Monte Carlo simulation, adding to each colliding parton an effective initial-state transverse momentum k_T with a Gaussian variance. The resulting growth of the LO cross section is characterized by a k_T-enhancement factor $K(p_T)$. At present, no such program is available for NLO calculations. However, to approximate the effects of supplemental k_T smearing on the inclusive NLO calculations for direct photon cross section, we estimate k_T-enhancement factors (as functions of p_T) for different values of $\langle k_T\rangle$ by computing ratios of the results from LO PQCD calculations [1] for different $\langle k_T\rangle$ values compared to results without k_T. These same k_T-enhancement factors are then applied to the results of NLO PQCD calculations [26,27].

Undoubtedly, this procedure involves a risk of double counting, since some of the k_T enhancement may already be contained in the NLO calculation. However, we expect such double counting effects to be small [26,27]. This k_T-smearing model has achieved considerable phenomenological success, since some authors [26,27] were able to accommodate both shapes and normalizations of direct photon and π^0 inclusive cross sections from E706, WA70, and UA6, for appropriate choices of $\langle k_T\rangle$ values consistent with data on high-mass pairs.

IV. COMPARISON OF DATA WITH THEORY

Both the CDF and DØ detectors at the Fermilab Tevatron $\bar{p}p$ collider have measured the photon inclusive cross section in the central region, $|\eta|<0.9$. The DØ experiment has also performed measurements in the forward region, $1.6<|\eta|<2.5$. The Collider Detector at Fermilab (CDF) data used in this analysis correspond to 90 pb^{-1} and 0.54 pb^{-1} of integrated luminosity at center of mass energies of 1.8 TeV and 630 GeV, respectively, and was recorded during 1994-1995 collider run [22]. The DØ measurements at $\sqrt{s}=1.8$ TeV result from the 1992–1993 running period and have an integrated luminosity of 107 pb^{-1} [24], while that at $\sqrt{s}$

$=630$ GeV were taken in the 1994–1995 run and represented 520 nb^{-1} of integrated luminosity [25]. Both CDF and DØ detectors identified photons as isolated energy clusters in their electromagnetic calorimeters by imposing the isolation criteria to suppress the background from bremsstrahlung photons and neutral meson decays. The CDF rejects events with a jet of transverse energy $E_T>1$ GeV in a cone of radius $R=\sqrt{\Delta\eta^2+\Delta\phi^2}=0.4$ around any photon candidate. The DØ requires the transverse energy to be less than 2 GeV in the annular region between $R=0.2$ and $R=0.4$ around the photon. The QCD calculations at NLO for the production cross section of direct photons are provided by Vogelsang [40] who used the latest updated parton distribution function CTEQ6M [31] and chose $\mu=p_T$ for the renormalization, factorization, and fragmentation scales.

In Fig. 1(a) we compare the transverse momentum (p_T) distribution of the DØ measurements of the isolated photon cross sections taken at $\sqrt{s}=1.8$ TeV during run 1b in the central ($|\eta|<0.9$) and the forward ($1.6<|\eta|<2.5$) rapidity regions with the corresponding theoretical calculations. Similarly, Fig. 1(b) compares the DØ data taken at $\sqrt{s}=630$ GeV in both central and forward regions with the corresponding NLO QCD predictions. Corresponding plots for the CDF results in the central region ($|\eta|<0.9$) for both the energies ($\sqrt{s}=1.8$ TeV and $\sqrt{s}=630$ GeV) are shown in Fig. 1(c). At first glance, it can be seen in the above figures that the NLO QCD predictions agree qualitatively well with the experimental results for both central and forward regions over a wide range of p_T with the exception of the low p_T end where the data points of the central region exhibit a steeper slope.

The discrepancy is more easily seen on a linear scale. In Fig. 2(a) we show the relative difference between the experimental and theoretical differential cross sections, (data-theory)/theory, versus p_T for the DØ and CDF measurements at $\sqrt{s}=1.8$ TeV in the central region. A reasonably good agreement is found between the NLO QCD predictions and the measured cross section at high p_T, $\geqslant 20$ GeV for CDF and $\geqslant 35$ GeV for DØ. However, at lower p_T values, the measured cross section exceeds the expectation from NLO QCD, a trend consistent with previous experience from the collider [20–25] and fixed-target [17–19] experiments. The DØ results exhibit larger deviations at low p_T than the CDF data, but show an excellent agreement with theory at high p_T. In the high-p_T region ($p_T>60$ GeV), the CDF data falls below the NLO QCD prediction by an overall normalization factor which is an unusual situation. The UA2 measurements at $\sqrt{s}=630$ GeV also show a similar deficit of photons at high p_T [22]. The run 2 data with higher statistics in this region will allow a better investigation of the high-p_T deficit. Similarly, Fig. 2(b) shows the p_T spectrum of (data-theory)/theory for the DØ and CDF data at $\sqrt{s}=630$ GeV in the central region. Here, we again observe that the DØ and CDF data agree remarkably well with the theory at high p_T ($\geqslant 20$ GeV), and at lower-p_T values there is an experimental excess of photons.

Figures 3(a) and 3(b) show the comparison of the measured direct photon cross section with the NLO theory using

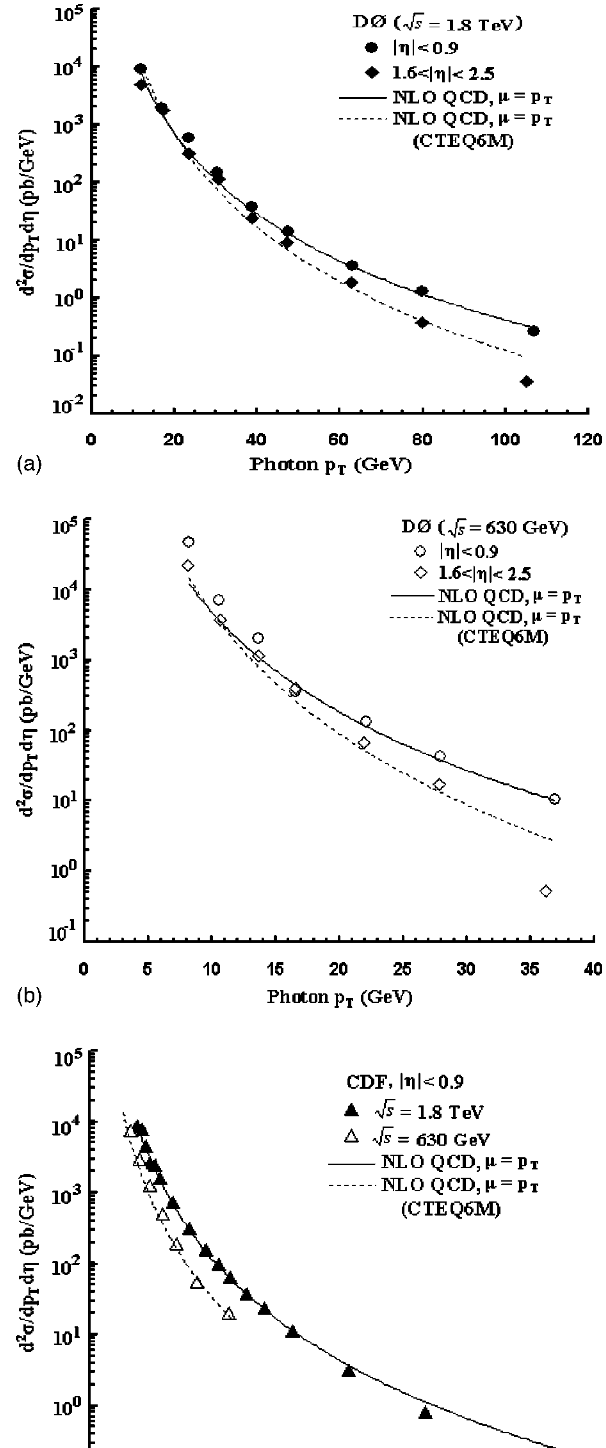

FIG. 1. The differential cross section for isolated photons as a function of transverse momentum p_T, measured by the DØ and CDF experiments. The curves show the corresponding next-to-leading order QCD calculations [40], using CTEQ6M parton distributions. (a) DØ data at $\sqrt{s}=1.8$ TeV in the central and forward regions. (b) DØ data at $\sqrt{s}=630$ GeV in the central and forward regions. (c) CDF data at $\sqrt{s}=1.8$ TeV and $\sqrt{s}=630$ GeV in the central region.

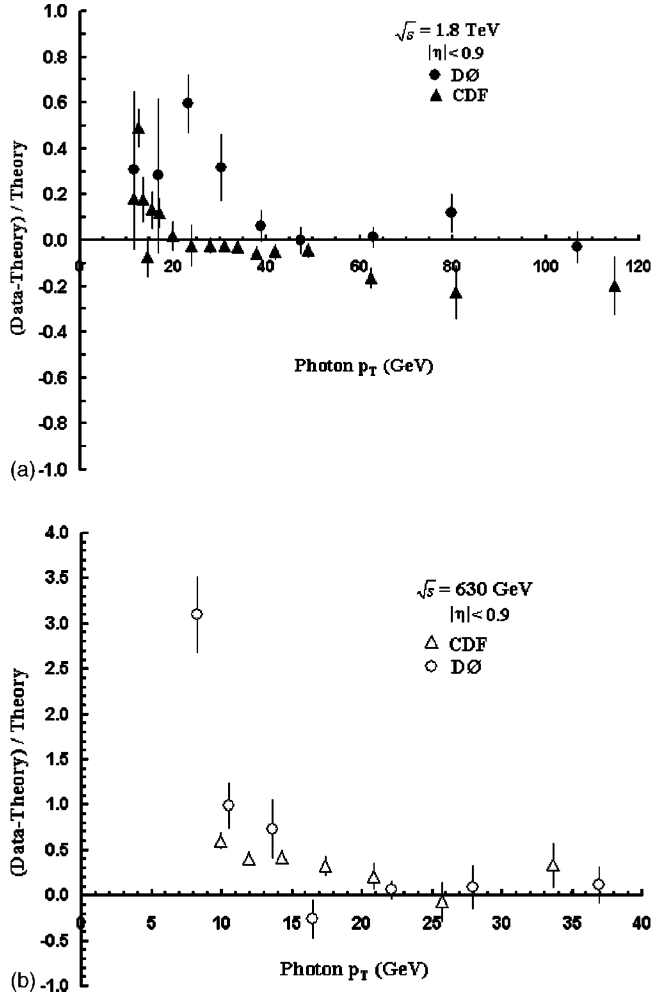

FIG. 2. The relative difference between the measured differential cross section for isolated photon production by the DØ and CDF Collaborations in the central region and the predictions from NLO QCD [40], using CTEQ6M parton distributions at (a) $\sqrt{s}=1.8$ TeV and (b) at $\sqrt{s}=630$ GeV. The error bars for the DØ data show the statistical and other uncorrelated uncertainties, while those for the CDF data show statistical uncertainty.

the CTEQ6M PDF for the DØ data in the forward rapidity region at $\sqrt{s}=1.8$ TeV and $\sqrt{s}=630$ GeV, respectively. The effects on theoretical predictions by changing the renormalization scales from $\mu=p_T/2$ to $\mu=2p_T$ are also shown. It is seen from the figures that the overall agreement of the measured cross sections with the theory is quite satisfactory over the whole range of p_T, taking into account the uncertainty due to the scale variations in the theoretical predictions.

Figures 4(a) and 4(b) show respectively the effect of different choices of the QCD scales on the NLO QCD calculations for the DØ data in the central rapidity region at $\sqrt{s}=1.8$ TeV and $\sqrt{s}=630$ GeV. The reference theoretical calculation includes CTEQ6M PDF and scales equal to p_T ($\mu=p_T$). The plots illustrate that the NLO calculations are quite sensitive to the choice of these scales which gives an indication of the importance of still higher-order contributions. We see that changing the scales from $\mu=p_T$ to $\mu=p_T/2$ or $\mu=2p_T$ changes the predicted cross sections by

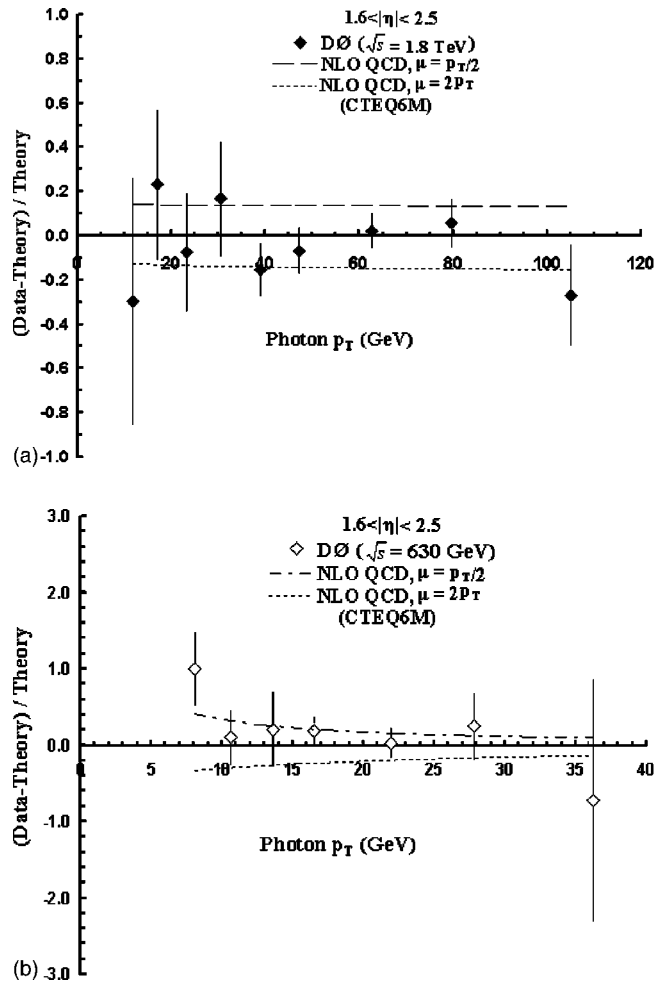

FIG. 3. Comparison of the measured isolated photon cross section by the DØ experiment in the forward region with the NLO QCD calculations [40], using CTEQ6M parton distributions at (a) $\sqrt{s}=1.8$ TeV and (b) $\sqrt{s}=630$ GeV. The error bars show the uncorrelated uncertainties. The effects on the comparison upon changing the renormalization scale in the theoretical predictions from $p_T/2$ to $2p_T$ are also shown.

10–15%, thus producing a small normalization shift throughout with almost no change in shape. The NLO results are found to be relatively insensitive to the changes in the factorization and fragmentation scales. From the above figures, it can be seen that it is possible to get a steeper slope at the low-p_T end by simultaneous variation of the renormalization (μ_{ren}), factorization (μ_{fact}), and fragmentation (μ_{frag}) scales independently [41], but only at the cost of an increase in the overall normalization. Apparently, it is not possible to get both the shape and the normalization correct by such a strategy. A similar result has also been obtained in the theoretical analysis of the CDF run 1b data [22,42].

The effect on the predicted cross section by using different choices of PDFs has been illustrated for several sets of PDFs, CTEQ5M1, CTEQ5M, CTEQ5HJ [43], Martin-Roberts-Stirling-Thorne (MRST99), MRST99($g\uparrow$), MRST99($g\downarrow$) [44], and MRST2001 [45]. The relative difference of the cross section between these sets of PDFs and the CTEQ6M parametrization for the DØ kinematics is shown in

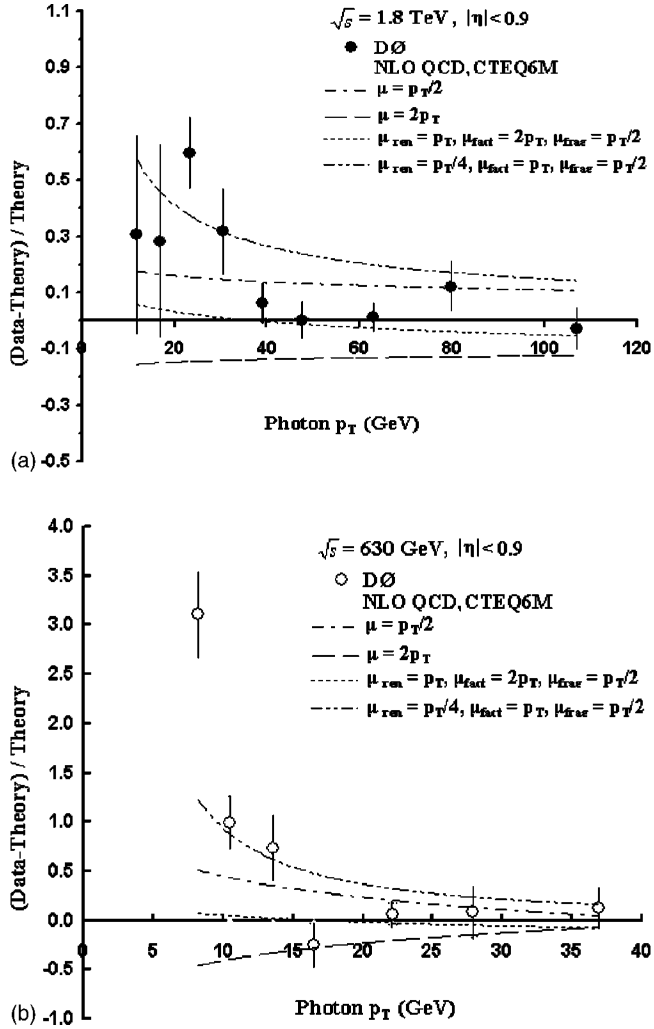

FIG. 4. Comparison of the DØ measurements of isolated photon cross section in the central region with the NLO QCD calcuations [40], using different choices of theoretical scales and CTEQ6M PDF at (a) $\sqrt{s}=1.8$ TeV and (b) $\sqrt{s}=630$ GeV.

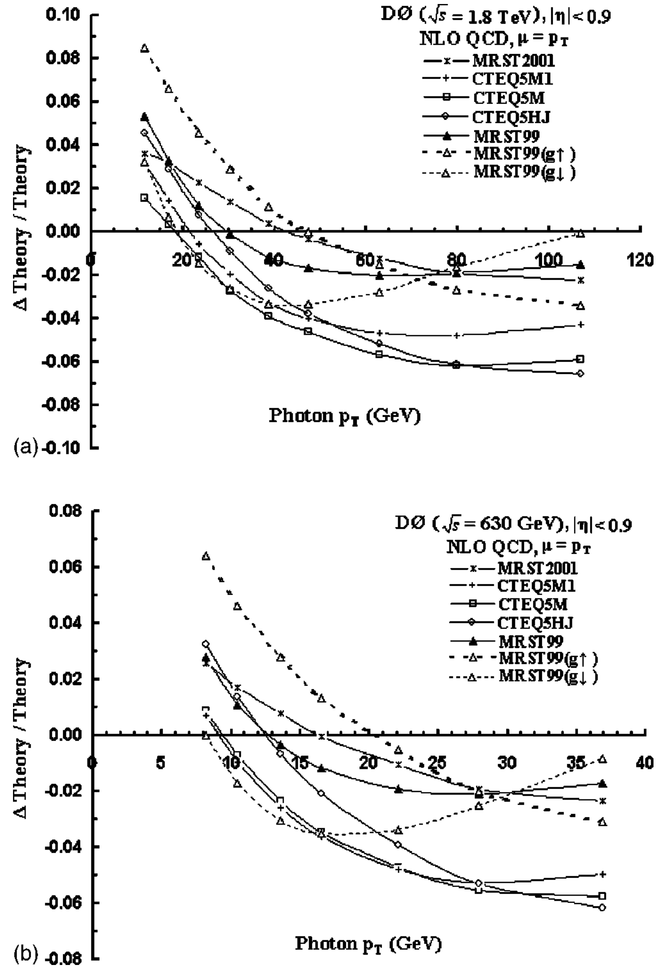

FIG. 5. The relative difference between the NLO QCD calculations for direct photon cross section for the DØ kinematical cuts due to different parametrizations of parton distribution functions. The reference PDF is CTEQ6M. All calculations use a scale of $\mu=p_T$ at (a) $\sqrt{s}=1.8$ TeV and (b) $\sqrt{s}=630$ GeV.

Figs. 5(a) and 5(b) at $\sqrt{s}=1.8$ TeV and $\sqrt{s}=630$ GeV, respectively. It is seen from the figures that the variation in the results is less than $\pm 9\%$ at $\sqrt{s}=1.8$ TeV and $\pm 7\%$ at $\sqrt{s}=630$ GeV. The theoretical uncertainty from the choice of PDFs is quite small and it is smaller than that from the scale dependence. It can be seen that it is not possible to improve the agreement with the data by making a fine-tuning of the parton distributions. The QCD analysis of the CDF run 1b data has also revealed similar results [22].

V. SIMULATION OF INITIAL-STATE SOFT-GLUON RADIATION

In QCD, initial-state radiation as well as final-state radiation of gluons are expected, which may generate large corrections to the overall topology of events. Within the framework of the perturbation theory, these radiation effects appear as higher-order corrections to the basic $2\rightarrow 2$ process. For the direct photon transverse momentum distribution, initial-state rather than final-state showering is most important. Especially at high center-of-mass energies, initial-state QCD radiation attains importance relative to fragmentation in determining the event structure due to increase in the phase space available for gluon emission [46]. As mentioned previously, the NLO PQCD calculations for direct photon cross section include effects due to single hard gluon only and is thus inefficient in describing the effects of additional multiple soft-gluon radiation from initial-state hard-scattering partons. The kinematics of the multiple partons in the initial-state shower may result in transverse momenta for the partons particularly in the hard scattering, effectively boosting the direct photon transverse momentum relative to the collinear approximation of the kinematics. Monte Carlo event generators such as PYTHIA can be used to investigate initial-state radiation effects as they provide a means to simulate complete event structure having detailed parton configuration with correct kinematics. In PYTHIA, all higher-order parton emissions are accounted for by the leading-log initial- and final-state parton showers, which includes simple parton branchings such as $q\rightarrow qg$, $g\rightarrow gg$, and $g\rightarrow q\bar{q}$ [39].

We examine the effects of multiple soft-gluon emissions

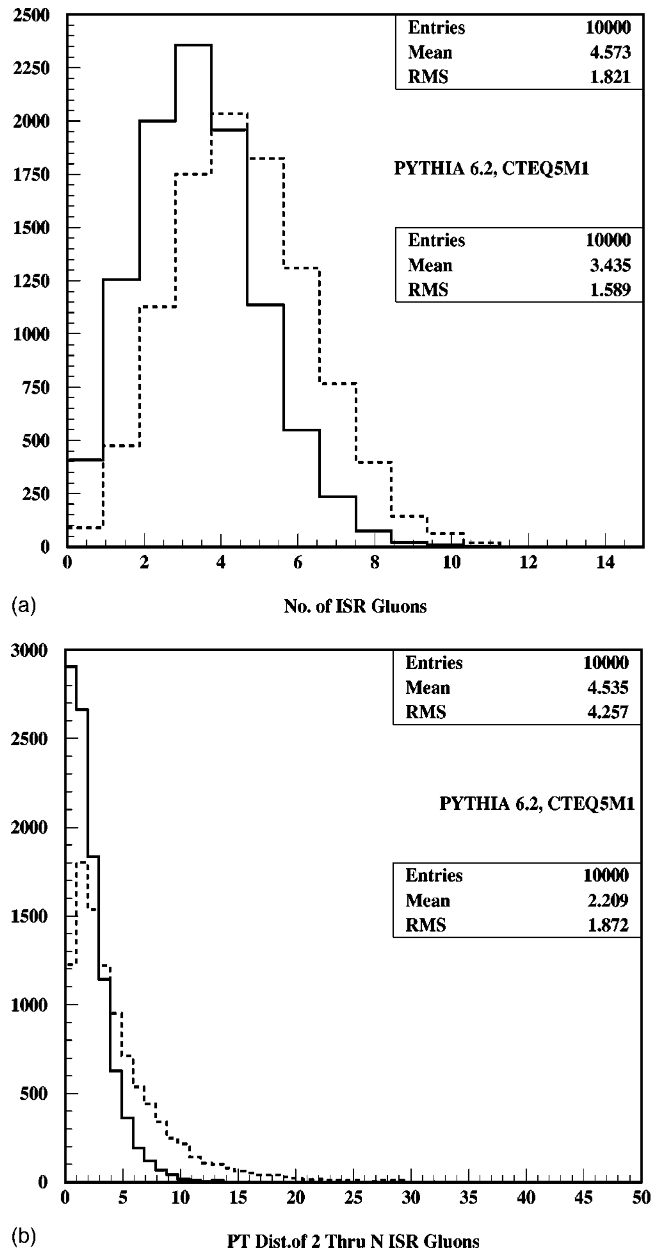

FIG. 6. ISR gluons associated with the direct photon events generated using PYTHIA in $p\bar{p}$ interactions at $\sqrt{s}=1.8$ TeV for $p_T^{min}=10$ (solid line) and 50 GeV (dotted line). (a) Number of ISR gluons. (b) Net p_T of the ISR gluons due to all but the leading ISR gluon.

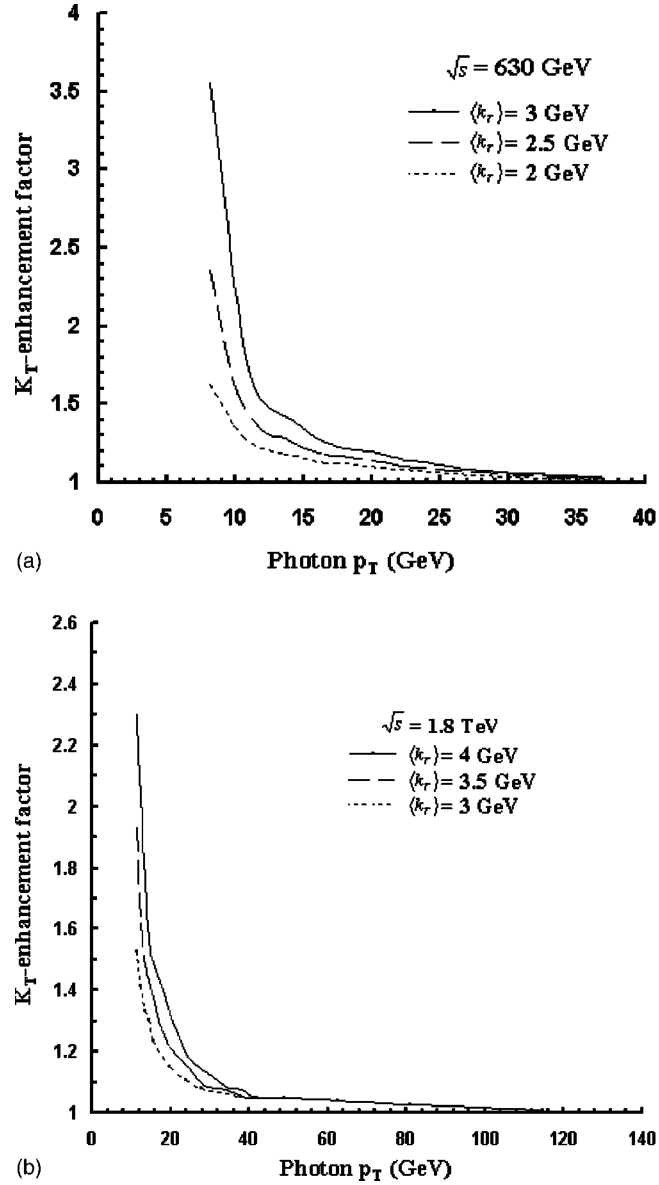

FIG. 7. The p_T spectrum of k_T-enhancement factor $K(p_T)$, associated with the LO calculations of direct-photon cross section using PYTHIA at (a) $\sqrt{s}=630$ GeV for $\langle k_T\rangle=2$, 2.5, and 3 GeV and (b) $\sqrt{s}=1.8$ TeV for $\langle k_T\rangle=3$, 3.5, and 4 GeV.

from the initial-state partons associated with the direct photon production using PYTHIA version 6.2 [39]. For this purpose, we simulate direct photon events in the $p\bar{p}$ interactions at $\sqrt{s}=1.8$ TeV and $\sqrt{s}=630$ GeV to extract the number of initial-state gluons as well as net k_T present in initial-state gluons, after subtracting the gluon with the highest initial state p_T. These results use default Gaussian primordial k_T distribution of 1 GeV for the partons inside the hadron (as would be the order expected from a purely nonperturbative hadronic finite size effects) and the initial-state radiation (ISR) switched on. Figure 6(a) shows the number of initial-state gluons in $p\bar{p}$ collisions at $\sqrt{s}=1.8$ TeV for two values of minimum p_T for hard process, p_T^{min} [CKIN(3) parameter in PYTHIA] $=10$ GeV and $=50$ GeV. The figure illustrates that the number of ISR gluons is significantly larger than the NLO PQCD approximation of either 0 or 1. The net k_T present in the ISR gluons, after subtracting the highest-p_T gluon, is shown in Fig. 6(b) for $p_T^{min}=10$ GeV and $=50$ GeV. As can be seen, the net p_T of such remnant gluons is ~ 2.2 GeV for $p_T^{min}=10$ GeV and increasing to ~ 4.5 GeV for $p_T^{min}=50$ GeV. Similar results are obtained for $p\bar{p}$ interactions at $\sqrt{s}=630$ GeV. In this case, the net p_T of ISR gluons beyond NLO turns out to be ~ 1.6 GeV for $p_T^{min}=10$ GeV and 2.3 GeV for $p_T^{min}=20$ GeV (not shown).

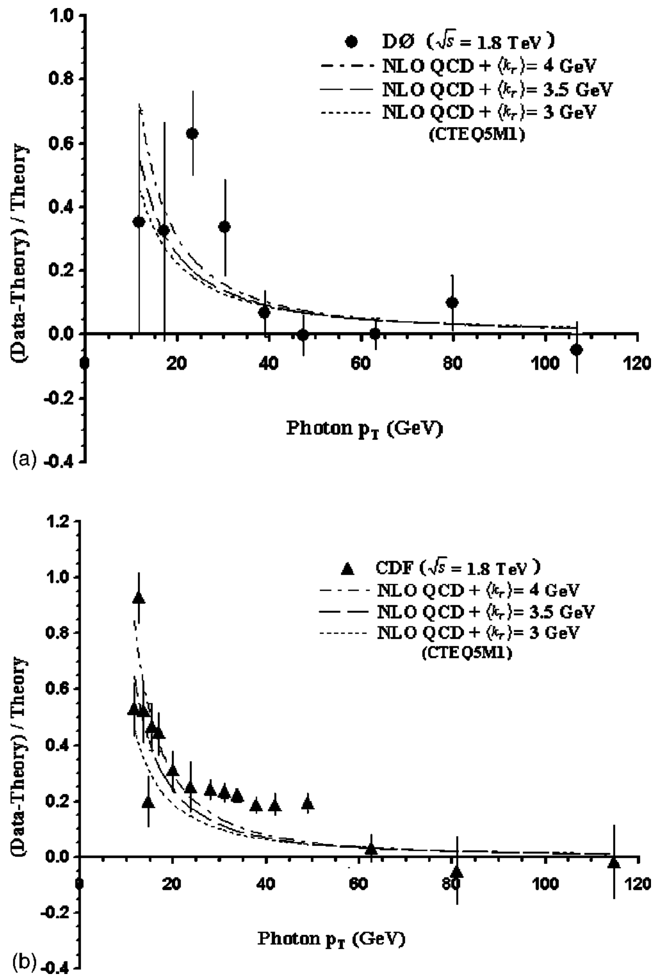

FIG. 8. Comparison of the isolated direct photon cross section at $\sqrt{s}=1.8$ TeV with the NLO QCD calculations without k_T and with k_T enhancement for $\langle k_T\rangle=3$, 3.5, and 4 GeV. (a) DØ run 1*b* data. (b) CDF run 1*b* data.

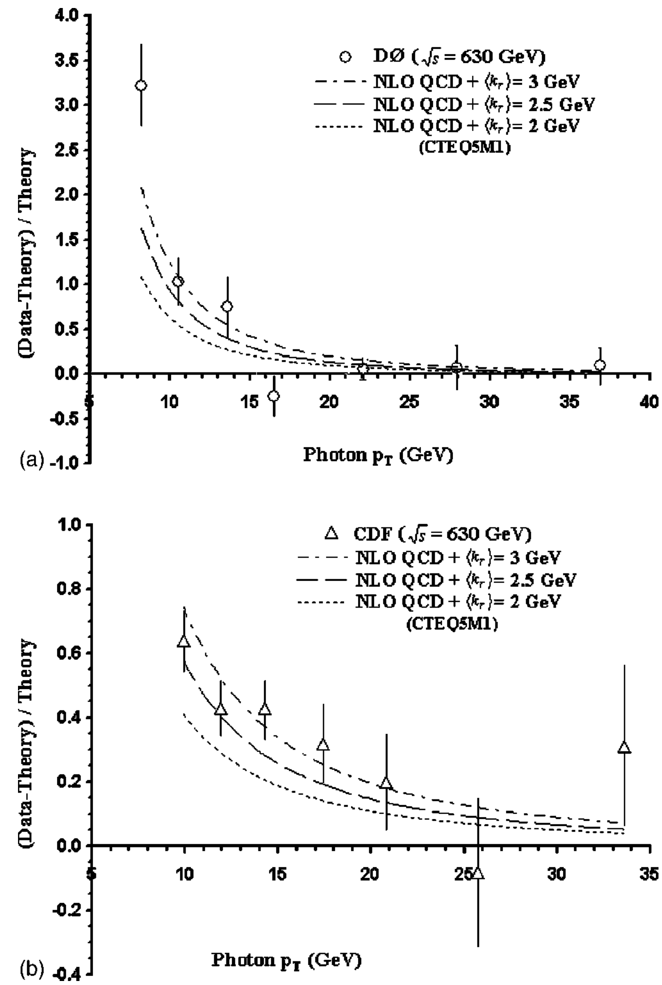

FIG. 9. Comparison of the isolated direct photon cross section at $\sqrt{s}=630$ GeV with the NLO QCD calculations without k_T and with k_T enhancement for $\langle k_T\rangle=2$, 2.5, and 3 GeV. (a) DØ data. (b) CDF data.

VI. APPLICATION OF k_T-SMEARING MODEL TO THE FERMILAB TEVATRON DATA

The previously described k_T-smearing approach is used to incorporate the effects of soft-gluon radiation in the calculated yields. PYTHIA 6.2 is employed to estimate the impact of parton k_T effects in the LO PQCD cross section of direct photons, wherein the incident partons have Gaussian distributed transverse momentum with an average value of k_T per parton ($\langle k_T\rangle$) being an adjustable parameter. The LO predictions uses the default PDF in PYTHIA 6.2, CTEQ5M1, and the renormalization scale, $\mu=p_T$. Figures 7(a) and 7(b) display respectively the k_T-enhancement factors $K(p_T)$ as a function of p_T at $\sqrt{s}=630$ GeV for values of $\langle k_T\rangle=2$, 2.5, and 3 GeV and at $\sqrt{s}=1.8$ TeV for values of $\langle k_T\rangle=3$, 3.5 and 4 GeV. These chosen values of $\langle k_T\rangle$ are consistent with that measured in the Drell-Yan process at each center-of-mass energy (3 GeV at 630 GeV, and 4 GeV at 1.8 TeV) [21]. Also, using diphoton production at the Fermilab Tevatron, the Collider Detector at Fermilab (CDF) has measured $\langle k_T\rangle=3.6\pm0.8$ GeV at $\sqrt{s}=1.8$ TeV [47]. As can be seen in Figs. 7(a) and 7(b), the k_T smearing, as expected, produces strong enhancement at low-p_T values, where p_T is not significantly larger than k_T. This effect diminishes rapidly with increasing p_T and is essentially negligible for $p_T\geqslant40$ GeV at $\sqrt{s}=1.8$ TeV and $p_T\geqslant25$ GeV at $\sqrt{s}=630$ GeV, thus exhibiting the expected $\approx1/p_T^2$ behavior.

Figures 8(a) and 8(b) show the comparison of photon cross section for the DØ and CDF run 1*b* data at $\sqrt{s}=1.8$ TeV for both with and without k_T enhancement, respectively. Similarly, Figs. 9(a) and 9(b) display the DØ and CDF measurements at $\sqrt{s}=630$ GeV. To incorporate the k_T effects, the existing NLO calculations (using CTEQ5M1 PDF and $\mu=p_T$) were multiplied by the k_T-enhancement factors $K(p_T)$. We see that the introduction of k_T smearing has a significant effect on the predicted cross sections and is successful to a great extent in describing both the normalization and the shape of the measured cross sections. The values of $\langle k_T\rangle=3$ GeV for 630 GeV and $\langle k_T\rangle=4$ GeV at 1.8 TeV provide reasonably good representations of both the CDF and DØ data. It is to be noted that the CDF data in Fig. 8(b) has been normalized upwards by a factor of 1.25 for the benefit of shape comparison. Without this normalization, the

CDF data lie below the theory at high p_T. It can be seen that the k_T smearing modifies only the lowest end of the p_T spectrum, where p_T is not significantly larger than k_T. Also, the dependence of $K(p_T)$ on $\langle k_T \rangle$ is especially strong at low p_T, which is consistent with the previous observations.

Although the present numerical results are only exploratory estimates of the size of expected effects, it is quite clear that the phenomenological consequences are significant.

VII. EXPECTATIONS FROM FERMILAB TEVATRON RUN 2

The run 2 of the Fermilab Tevatron collider at $\sqrt{s} = 1.96$ TeV with increased luminosity and the upgraded CDF and DØ detectors has the potential to significantly refine our understanding of inclusive isolated direct photon production. The kinematic reach in transverse momentum should be greatly extended and the statistical and systematic precision of the data will also be increased, compared to run 1. These measurements will allow both the low-p_T and the high-p_T regions to be investigated thoroughly and precisely. The possibility that the discrepancy between data and theory may be dependent on rapidity is interesting and is one that can also be investigated in more detail. Although the data are not expected to improve directly the knowledge of the gluon distribution at intermediate and large x, it can do so by providing a testing ground for newly developed theoretical models and formalisms signifying the role of multiple gluon emission in the direct photon process, and therefore can help resolve the present arguments. Once this physics is properly understood, the existing fixed-target data should provide one of the best constraints on the gluon density, as has been envisioned for a long time.

VIII. CONCLUSIONS AND DISCUSSION

Direct photon production has proved extremely interesting and remained quite controversial. In this paper, we have analyzed the p_T spectrum of the CDF and DØ measurements of direct photon cross section at $\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 630$ GeV. The experimental data has been confronted with the NLO QCD calculations using the latest updated set of PDF, CTEQ6M with the conventional choice of scales. These datasets in the central rapidity region exhibit a steeper slope than the theoretical estimates at low p_T. Many variations of the recently improved PDFs and the QCD scales were tried, with small changes in the shape of the predictions, but none actually predicted the shape of the measured cross sections. The effects of initial-state soft-gluon radiation on the direct photon production have been investigated using a phenomenological k_T-smearing model, which supplements the NLO calculations with a simplified Gaussian smearing. It was found that the inclusion of k_T effects into the theoretical predictions yield a significantly better description of the Fermilab Tevatron data. Although these results cannot be interpreted as a QCD prediction because of many uncertainties (owing to the model dependent assumptions) in the present implementation of k_T kick, they can be interpreted as an existence of the proof that higher-order QCD contributions (particularly from the initial-state soft-gluons) can account for the theory vs data discrepancy. A definitive conclusion regarding the quantitative role of the k_T effects in the hard scattering awaits a more rigorous theoretical treatment of the soft-gluon radiation. A more developed theoretical framework is crucial for an accurate determination of gluon distribution in the hadrons, especially in the large-x region where significant uncertainties remain.

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