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Photon-jet correlations and constraints on fragmentation functions

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We study the production of a large-p_T photon in association with a jet in proton-proton collisions. We examine the sensitivity of the jet rapidity distribution to the gluon distribution function in the proton. We then assess the sensitivity of various photon + jet correlation observables to the photon fragmentation functions. We argue that RHIC data on photon-jet correlations can be used to constrain the photon fragmentation functions in a region which was barely accessible in LEP experiments.

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I. INTRODUCTION

The phenomenology of prompt photons is very rich and interesting, as the photon on one hand can be considered as a pointlike particle described by QED, leading to clean experimental signatures. On the other hand, the photon is also involved in hadronic phenomena, like the fragmentation of an energetic parton into a large-p_T photon and hadronic energy.

At the LHC, photon + jet final states will be important for jet calibration and parton distribution function (pdf) studies [1–6]. Diphotons will play an important role in the search for a Higgs boson with mass below ~140 GeV, where the decay into two photons is a very prominent channel [7,8], for which the branching ratio is small, $\sim\mathcal{O}(10^{-3})$, and the signature is provided by a narrow peak over a huge background involving various components. Besides the so-called irreducible background from prompt diphotons, the background called reducible comes from photon-jet and jet-jet events, with the jet faking a photon in various possible ways (high p_T π^0 or other neutral hadrons, charged particles inducing the radiation of energetic photons e.g. by bremsstrahlung due to interactions with innermost layers of the detector, etc.). An accurate knowledge of the photon + jet rate, in particular, is required to estimate and control the reducible background to the Higgs boson search in the diphoton channel [9]. In addition, highly energetic photons are important signatures for various scenarios of physics beyond the standard model. Therefore, issues like controlling photon isolation or further constraining the parton-to-photon fragmentation functions are of major importance, and data from RHIC and the Tevatron should be exploited as much as possible to this aim.

The production of prompt photons in hadronic collisions may be schematically seen as originating from either of two mechanisms. In the first one, which may be called "direct" (D), the photon behaves as a high p_T colorless parton, i.e. it takes part in the hard subprocess, and is most likely well separated from any hadronic environment. In the other one, which may be called "fragmentation" (F), the photon behaves hadronlike, i.e. it results from the collinear fragmentation of a colored high p_T parton. In the latter case, it is most probably accompanied by hadrons—unless the photon carries away most of the transverse momentum of the fragmenting parton.

From a technical point of view, (F) emerges from the calculation of the higher order corrections in the perturbative expansion in powers of the strong coupling α_s. At higher orders, final state collinear singularities appear in any subprocess where a high p_T outgoing parton of species k (quark or gluon) undergoes a cascade of successive collinear splittings together with the collinear emission of a photon. The higher order corrections to the cross section can be split into (1) a contribution free from these final state collinear singularities, to be added to the Born term so as to build (D), and (2) a contribution (F) involving these singularities together with accompanying large collinear logarithms. In (F), the final state collinear singularities and accompanying logarithms can be factorized to all orders in α_s from short distance terms according to the factorization theorem and absorbed into fragmentation functions of parton k to a photon $D_{\gamma/k}(z, M_F^2)$. Let us mention, however, that the splitting of the cross section between (D) and (F) is not unique and that the $D_{\gamma/k}(z, M_F^2)$ depend on the arbitrary factorization scheme specifying which nonsingular parts are factorized together with the collinear singularities; the latter depend, in particular, on some arbitrary fragmentation scale M_F. We therefore need to define the scheme used. In this article, (D) is defined as the Born term plus the fraction of the higher order corrections from which final state collinear singularities and accompanying collinear logarithms have been subtracted according to the $\overline{\text{MS}}$ factorization scheme. (F) is defined as the contribution involving a fragmentation function of any parton into a photon defined in the $\overline{\text{MS}}$ scheme. The partonic cross section can thus be written schematically as

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$$d\sigma^{\gamma} = d\sigma^{(D)}(\mu^2, M^2, M_F^2) + \sum_{k=q,\bar{q},g} d\sigma_k^{(F)}(\mu^2, M^2, M_F^2) \otimes D_{\gamma/k}(M_F^2), \quad (1.1)$$

where μ, M, M_F are, respectively, the (arbitrary) renormalization, initial state factorization, and final state fragmentation scales, and "$\otimes$" stands for a convolution over the fragmentation variable. The pointlike coupling of the photon to quarks is responsible for the well-known anomalous behavior of $D_{\gamma/k}(z, M_F)$, roughly as $\alpha_{\rm em}/\alpha_s(M_F^2)$, when the fragmentation scale M_F, chosen of the order of a hard scale of the subprocess, is large compared to $\mathcal{O}(1 \text{ GeV})$. More generally, while the M_F evolution of these fragmentation functions is given by inhomogeneous evolution equations whose kernels are computable in perturbative QCD, the z profiles of these fragmentation functions are not fully predictable from perturbative QCD. These parton-to-photon fragmentation functions therefore either have to be modeled in some way and/or constrained using experimental data.

The fragmentation component represents a fraction of the inclusive prompt photon signal which grows with the center-of-mass energy of the collision. While it remains subleading at fixed target energies, it becomes dominant at collider energies. On the other hand, most collider experiments—apart from the PHENIX experiment at RHIC [10], but, in particular, the TeV collider experiments CDF and D0 at the Tevatron, ATLAS and CMS at the LHC—do *not* measure inclusive photons, because at these energies the inclusive prompt photon signal would be swamped by a large background of secondary photons from decays of fast neutral mesons (mainly π^0, as well as η, etc.). Instead these experiments impose isolation criteria on the hadronic final states of photon candidate events, requiring that the photon be not accompanied by more than a prescribed amount of hadronic transverse energy in some given cone about the photon. An analogous[1] criterion can be implemented in parton level calculations. The isolation cuts do not only suppress the background, they also substantially reduce the (F) component. Yet some fraction of the (F) component may survive and affect shapes of various tails of distributions, especially for correlation observables. Of course the sensitivity is even larger when loose isolation cuts are applied. In this article we wish to stress the interest of photon-jet correlation observables, in particular, in constraining the photon fragmentation functions, which requires to go beyond the lowest order. Similar studies have been performed in Ref. [11]. However, in these works the (F) component was calculated at lowest order (LO) only.

[1]The experimental request may also impose a veto on charged tracks in the vicinity of the photons. However, such vetoes cannot be implemented in partonic level calculations: a full description of the hadronized final state would be necessary.

In a previous article [12] we proposed a critical reexamination of the status of single prompt photon production in hadronic collisions in light of recent experiments, which was based on a next-to-leading order (NLO) calculation of both (D) and (F) provided in the form of a partonic Monte Carlo code, JETPHOX [13]. The present paper aims at supplementing this previous work with a study of photon-jet correlations using the same tool, for the presentation of which we refer to [12]. The article is organized as follows. In Sec. II, we examine the magnitude of the fragmentation component on the photon-jet angular distribution at the Tevatron. In Sec. III we discuss the jet rapidity distribution in photon + jet associated production, as a possible way to help constrain the uncertainties on the gluon distribution function. In Sec. IV we then discuss the potential of photon-jet correlations measured at RHIC without isolation as a tool to constrain the photon fragmentation functions. Finally, Sec. V gathers our conclusions. A similar study dedicated to fragmentation into hadrons will be discussed in a future article.

II. PHOTON-JET ANGULAR DISTRIBUTION

An observable expected to receive a distinctive contribution from the (F) component is the photon-jet angular distribution which has been measured by the CDF Collaboration [14,15] and is defined as follows.

At LO, corresponding to $2 \rightarrow 2$ kinematics, $\cos\theta^*$ is the cosine of the angle between the photon direction and the beam axis in the center-of-mass system of the partonic subprocess. It also coincides with $\cos\theta^* = \tanh y^*$ where $y^* = (y_\gamma - y_{\rm jet})/2$. This angular distribution is expected to receive a dominant contribution from the (F) component when $\cos\theta^*$ becomes close to 1. Indeed, at lowest order, the (D) component proceeds via a t-channel quark exchange yielding a behavior $\sim 1/(1 - \cos\theta^*)$ for the partonic amplitude squared, whereas the (F) component involves also gluon exchange in the t channel, yielding a behavior $\sim 1/(1 - \cos\theta^*)^2$. On this ground, one thus expects (F) to take over for $\cos\theta^*$ values close enough to 1.

Depending on the cuts applied, the $\cos\theta^*$ dependences coming from the partonic transition matrix element squared may be blurred by an extra dependence coming through the parton luminosity. Focusing on the direct (D) contribution, and parametrizing the LO phase space as

$$d(p_T^\gamma)^2 dy_\gamma dy_{\rm jet} = \tfrac{1}{2} d(p^*)^2 dy_B d\cos\theta^* \quad (2.1)$$

in terms of the variables $\cos\theta^* = \tanh y^*$, $y_B = (y_\gamma + y_{\rm jet})/2$, and $p^* = p_T^\gamma \cosh y^*$, the LO distribution in $\cos\theta^*$ reads

$$\frac{d\sigma}{d\cos\theta^*} = \sum_{i,j} \int dy_B dp^* G_{i/P}(x_i) G_{j/\bar{P}}(x_j) \frac{d\hat{\sigma}_{ij}}{d\cos\theta^* dy_B dp^*} \quad (2.2)$$

with

$$x_{i,j} = \frac{2p^*}{\sqrt{S}} e^{\pm y_B}. \tag{2.3}$$

In particular, one of the two pdfs involved in the distribution in $\cos\theta^*$ has an argument x which grows with y^* i.e. with $\cos\theta^*$ at fixed p_T^γ, so that this pdf decreases (towards zero) if $\cos\theta^*$ increases (towards one). In the absence of extra cuts, this decrease actually takes over the growth of the partonic cross section with growing $\cos\theta^*$ over the whole range. At LO, this can be neutralized by imposing cuts on y_B and p^* independent from y^* [14,15], so that the integration over y_B and p^* in Eq. (2.2) yields $\cos\theta^*$ independent factors. A similar procedure and conclusion hold for the fragmentation (F) component, at least in the absence of isolation.

Beyond LO the definition of $\cos\theta^*$ has to be extended. This extension is not unique, and various definitions can be found in the literature. Here we take[2]

$$\cos\theta^* = \tanh y^*, \tag{2.4}$$

where

$$y^* = \tfrac{1}{2}(y_\gamma - y_{\text{leading jet}}), \tag{2.5}$$

$y_\gamma - y_{\text{leading jet}}$ being the difference[3] between the rapidity of the photon and the rapidity of the *leading* jet, i.e. the jet of highest transverse energy. Furthermore, the higher order contributions to the angular distribution involve an extra convolution smearing over kinematical configurations, so that the interpretation of this distribution beyond LO is less transparent.

Besides, measurements at colliders most often involve isolated photons, in which case the (F) component is quite reduced. Namely, when the hadronic transverse energy accompanying the photon is required to be smaller than $E_{T\,\max}$, the (F) contribution is roughly proportional to $(1 - z_c) \simeq E_{T\,\max}/p_T^\gamma$, the width of the support $[z_c, 1]$ of the convolution with the photon fragmentation functions. If $E_{T\,\max}$ is chosen such that this ratio is always small, the dominance of the t-channel gluon exchange from the (F) component is never effective; yet one might still expect a sizable distortion of the angular distribution for $\cos\theta^*$ close enough to 1. We note also that if $E_{T\,\max}$ does not scale with p_T^γ, the isolation constraint implied on the fragmentation variable z, $z \geq z_c$ with

$$1 - z_c \simeq \frac{E_{T\,\max}}{p^*} \frac{1}{(1-\cos^2\theta^*)^{1/2}} \tag{2.6}$$

induces, through the convolution over z, an extra dependence on $\cos\theta^*$ which contorts (amplifies somewhat) the growth of the (F) contribution provided by the partonic transition matrix elements alone.

In a preliminary study [15] subsequent to the analysis published in [14] and based on a data set with larger statistics and extended towards lower values of p_T^γ, the CDF Collaboration found a discrepancy between the measured $\cos\theta^*$ distribution and the theoretical prediction of [11]. This subsequent preliminary CDF analysis concluded that extra dijetlike contributions involving t-channel gluon exchange would be necessary to bridge the gap, and that these extra contributions might come from NLO contributions to the (F) component. Since the prediction of [11] involves an account of (F) at LO only, we have revisited this observable and computed the effects of accounting for (F) at NLO. The CDF Collaboration adopted a procedure to patch together the contributions from data corresponding to two regions that were distinct in p^* and y_B though overlapping in $\cos\theta^*$, in order to maximize the range in $\cos\theta^*$ displayed on one and the same plot. In particular the distribution was normalized to 1 in the bin farthest from $\cos\theta^* = 1$, and the data sets from the two regions were normalized to each other in one overlapping bin in $\cos\theta^*$. We understand this approximate procedure to have been dictated by the use of limited statistics and precision of Run I data but we did not follow the same procedure in our study for several reasons. First, the normalization to 1 in the bin farthest from $\cos\theta^* = 1$ aims at getting rid of the numerical factor coming from the integration of partonic luminosity. This is fine as long as only one partonic subprocess contributes—or at least, when one yields a much greater contribution than all the others. However, in the present case, the distribution is of the form

$$\frac{d\sigma}{d\cos\theta^*} = \sum_s \mathcal{L}^{(s)} \frac{d\hat{\sigma}^{(s)}}{d\cos\theta^*}, \tag{2.7}$$

i.e. a linear combination of contributions coming from several subprocesses s. In particular, considering (D) only, gq (or $g\bar{q}$) initiated and $q\bar{q}$ initiated processes which contribute at LO have distinct functional dependences on $\cos\theta^*$. Second, the integrated partonic luminosity factors $\mathcal{L}^{(s)}$ depend not only on the subprocess s but also on the integration regions in phase space. The relative weights of the subprocesses from the contributions (D) and (F) thus differ in the two regions defined by CDF as "1" and "2." The normalization enforced by the matching procedure of CDF is not harmless on the impact of the NLO correction to the (F) contribution, and might *reduce* the impact of this correction.

Therefore we did not stick to the CDF study. We focused on a study of the magnitude of the (F) contribution, without making a direct comparison with the CDF Run I data. Our study has been made for $\sqrt{S} = 1.96$ TeV, with the following definitions and kinematic cuts: $|y_\gamma| \leq 0.9$,

[2] An alternative possibility is the one used in [14], which, in short, combines several jets of a multijet final state into one so-called superjet recoiling against the photon, in order to stick to a $2 \to 2$ kinematics as close as possible. See [14] for more details.

[3] Note that the definition of $\cos\theta^*$ given by (2.4) and (2.5) refers to a quantity which is invariant under longitudinal boosts along the beam axis.

$p_T \geq 30$ GeV, $p_T^{\text{leading jet}} \geq 25$ GeV. The jets were defined according to the D0 midpoint algorithm [16], with cone aperture $R_c = 0.7$. The photon isolation required that in a cone of aperture $R = 0.4$ in rapidity and azimuthal angle around the photon direction, the fraction of maximal hadronic transverse energy $E_{T\,\max}/p_T^\gamma$ be less than a prescribed value ϵ, which we varied from 0.05 to 0.3. The further cut 45 GeV $\leq p^* \leq$ 55 GeV was imposed. The pdf set CTEQ 6.1 was used together with the BFG set II for the fragmentation functions, with the scale choice $\mu = M_F = M = p_T^\gamma/2$.

We have considered three ingredients which may affect the size of the contribution of the (F) component. One is the account for the NLO corrections to the many subprocesses; another one concerns the uncertainty on the fragmentation functions; yet another one deals with a possible mismatch between the implementation of isolation at the partonic vs hadronic level.

Let us first consider the impact of the NLO corrections to the (F) component. For the standard scale choice $\mu = M_F = M = p_T^\gamma/2$, the effect is to multiply the component (F) at LO by about a factor of 2. From the top-right Fig. 1, the impact on the total (D) + (F) both at NLO amounts to an increase by 4% in the upper $\cos\theta^*$ range with respect to (w.r.t.) (D) at NLO + (F) only at LO for $\epsilon = 0.05$.

Is it possible to increase the (F) contribution by modifying the fragmentation functions? When a stringent isolation cut is required on the photon candidates as in the CDF experiment, the (F) contribution involves the photon fragmentation function at $z \geq z_c$ i.e. rather close to 1. In this region the fragmentation functions are dominated by their so-called anomalous parts predicted by perturbative QCD. Their poorly known nonperturbative parts, which would be the only adjustable ingredients, play no role: thus the (F) contribution to the $\cos\theta^*$ distribution is rather tightly constrained.

We have tackled the issue of the account of isolation at the partonic vs hadronic level by varying the value of the isolation parameter ϵ from 0.05 to 0.3. As already mentioned in Table 2 of [17] in the case of the inclusive cross section and as can be seen on Fig. 1, the separate (D) and (F) contributions do depend strongly on ϵ at NLO; yet strong cancellations turn out to occur between (D) and (F) so that the total (D) + (F) depends on ϵ only very mildly, at least as long as the infrared sensitive term $\alpha_s \ln\epsilon$ in (D) does not become large—otherwise the fixed order prediction becomes unreliable. Therefore, changing the calorimetric isolation parameter by as much as a factor of 6 does not modify the total contribution to the $\cos\theta^*$ distribution significantly.

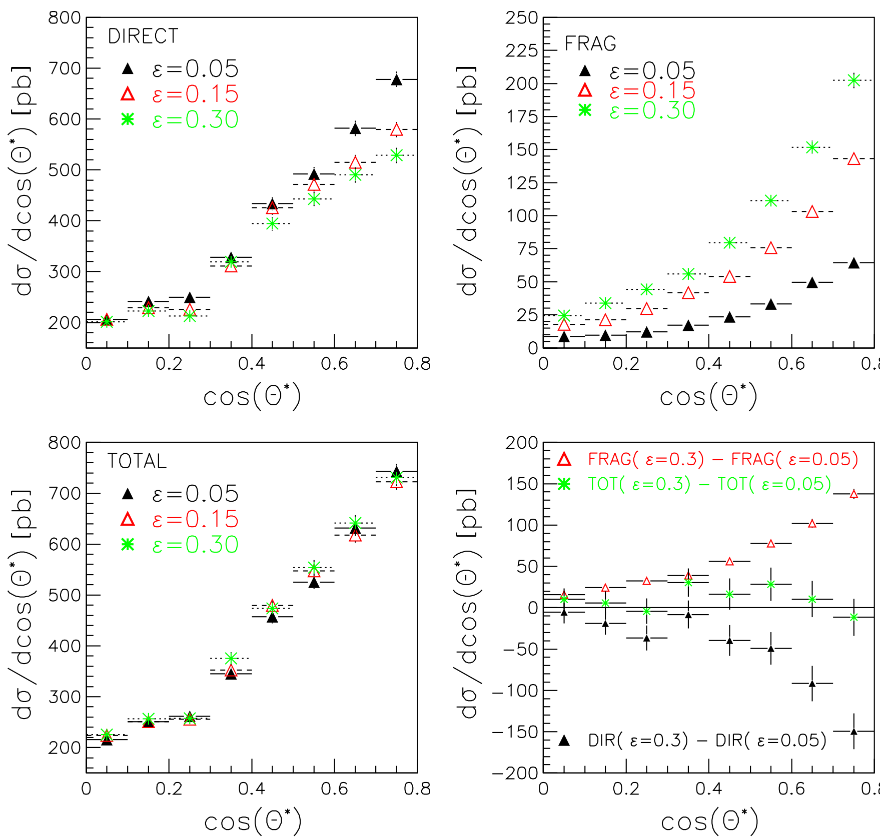

FIG. 1 (color online). Sensitivity of the distribution of $\cos\theta^*$ in photon + jet at NLO to the isolation parameter $\epsilon = E_{t\,\max}/p_T^\gamma$. Top left: Direct (D) contribution only. Top right: Fragmentation (F) contribution only. Bottom left: total (D) + (F) contribution. Bottom right: differences in (D), (F) and total (D) + (F) between $\epsilon = 0.3$ and 0.05.

To summarize, the results of our calculations show that the idea of playing with the fragmentation component as suggested in the CDF analysis turns out to be ineffective in the conditions which we have considered. It would be worthwhile to perform a quantitative analysis of the much larger statistics data set gathered in Run II, without relying on the questionable matching procedure used in the CDF Run I analysis.

Let us recall that, beyond the isolation requirements and the refined analysis to improve background rejection, the CDF measurement of isolated photons required the statistical subtraction of a contamination of photon candidates coming from neutral hadrons—mainly π^0, plus η, ρ^0, ω, etc. The background was removed statistically by exploitation of the expected difference in the resulting shower profiles or by the different conversion probabilities using Monte Carlo simulations [18]. The latter relied on hadronization models suited to describe the bulk of hadronization. On the other hand, the *very small* fraction of hadronic events which pass the isolation cuts corresponds to the tail of fragmentation at large z which is not constrained by the data. These background events yield, namely, dijet-type contributions involving t-channel gluon exchange, which might explain part of the discrepancy observed, and the distribution in $\cos\theta^*$ at $\cos\theta^* \to 1$ might provide an enhanced sensitivity to this contamination w.r.t. other prompt photon observables.

Let us add a comment on the comparison with the situation for the photon-photon azimuthal angle distribution in photon pair production [19]. In the latter case, some of the higher order contributions involving one direct photon and one photon from fragmentation provided a collinear logarithmic enhancement at low azimuthal angle, when a hard jet recoils against the photon pair at low relative angle. No such phenomenon occurs in the photon-jet case, since the jet considered in that observable is always the leading jet of the event which roughly recoils against the photon.

III. JET RAPIDITY DISTRIBUTION

Despite years of intense work, a proper understanding of the uncertainties on the gluon distribution function is still lacking [20]: due to shape assumptions, one can find some regions with small errors despite the lack of data points. More precisely, as shown by [21], uncertainties on the gluon distribution at very low x ($x \leq 10^{-4}$, where there are no constraining experimental data points) obtained by CTEQ6.5 and MRST2001e do not overlap. More flexible shapes modeled with neural networks and fitted using a genetic algorithm from NNPDF [22] give much larger error bands overlapping with the ones from CTEQ and MRST. We note that dynamical PDFs generated radiatively from valencelike input at low scales may be another approach which yields smaller uncertainties, [23], see also Fig. 3 of [24].

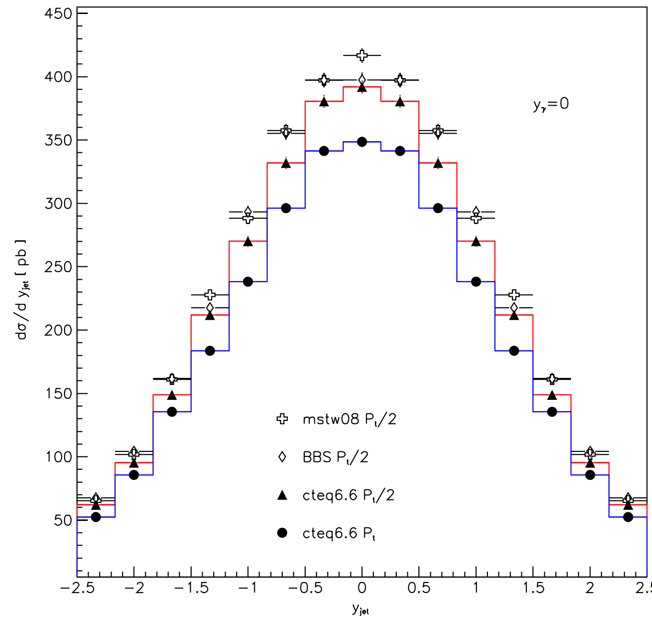

FIG. 2 (color online). Distribution of leading jet rapidity in photon + jet associated production, at $y_\gamma = 0$ for various pdf sets and scale choices.

Is it possible to be less sensitive to shape assumptions by using photon + jet correlations? The Tevatron experiments CDF and D0 both during Runs I and II, have been measuring photon-jet correlations, which explore the short distance dynamics in a more constrained way than inclusive photon production. A recent comparison between D0 data and JETPHOX has been performed [25] for the distribution $d\sigma/dy^\gamma$ vs p_T^γ. An interesting study[4] [26] of the possibilities of the CMS experiment on this distribution has recently appeared. Among the other correlations which can be studied, let us mention the distribution of jet rapidity at fixed photon rapidity, integrated over the photon transverse momenta above some $p_{T\,\mathrm{min}}^\gamma$. At large rapidities, the main contribution comes from the subprocess $qg \to q\gamma$ (or $\bar{q}g \to \bar{q}\gamma$) where the initial state gluon is at quite low x, down to $\mathcal{O}$ (a few 10^{-3}) while the x of the initial state (anti) quark is $\sim\mathcal{O}(10^{-1})$. This correlation observable is thus sensitive to gluons in a low x region overlapping with the one explored at HERA.

Figures 2 and 3 show the JETPHOX predictions for various pdf sets for the distribution of jet rapidity, for the photon rapidities $y_\gamma = 0$ and 2.5, respectively, at the Tevatron for $\sqrt{S} = 1.96$ TeV. The jets are defined according to the D0 midpoint algorithm with cone aperture $R_C = 0.7$ [16], and the discussion at NLO refers to the leading jet i.e. the jet with highest p_T. The cross section is integrated over photon transverse momenta larger than 30 GeV and over jet p_T larger than 20 GeV. The choice of scales is

[4] Yet we notice that this study accounts for the fragmentation contribution at LO only.

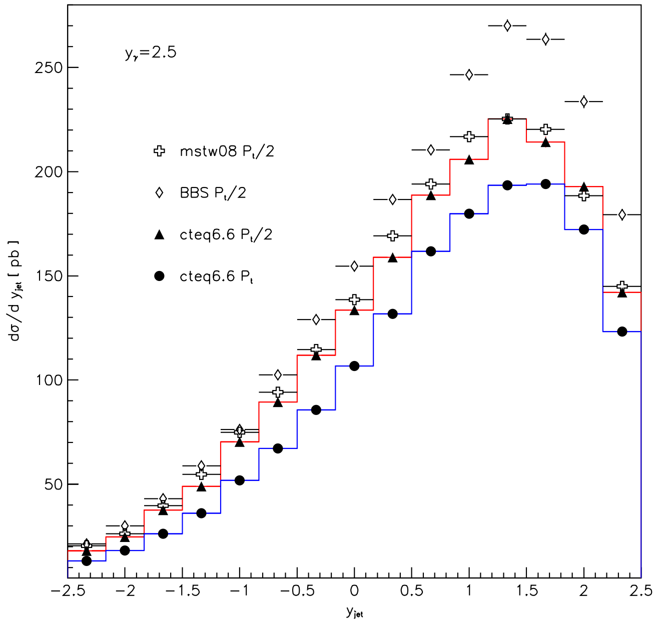

FIG. 3 (color online). Distribution of leading jet rapidity in photon + jet associated production, at $y_\gamma = 2.5$ for various pdf sets and scale choices.

$\mu = M = M_F = p_T^\gamma/2$. Besides the prediction using[5] the pdf sets CTEQ 6.6 [28] and MSTW08 [29] resulting from global fits, we also show the prediction with the BBS set [30], an example of a set modeled through dynamical generation, which has a quite different gluon pdf in the low x region, to illustrate the sensitivity of this observable to low x gluons. However, we cannot draw any definite conclusions from this observable alone since the dependence of these predictions on the scale choice at NLO is as large as the spread with respect to the various pdfs used. An error analysis taking into account the detailed information provided by MSTW08 is beyond the scope of this paper.

IV. THE PHOTON FRAGMENTATION FUNCTION

The large-p_T photon-jet correlations also give access to the photon fragmentation function (PFF) which has rarely been measured. Actually only two LEP experiments, ALEPH [31] and OPAL [32] measured the PFF. However, it is difficult to observe a photon in a large hadronic background and hence the PFF has mainly been measured for large values of $z = 2E_\gamma/\sqrt{s}$. Good agreement is found between these data and two NLO theoretical results [27,33]. The semi-inclusive case of the photon-within-a-jet fragmentation function is not considered here. It has been studied in Refs. [34,35] in connection with LEP data.

The hadroproduction of large-p_T photons and jets should also allow to measure the PFF. First let us consider the direct subprocess $qg \to q\gamma$ in which the final photon transverse momentum p_T^γ is balanced by the q-jet transverse momentum $p_T^{\rm jet}$ such that $z_\gamma = -\frac{\vec{p}_T^{\,\gamma}\cdot\vec{p}_T^{\,\rm jet}}{||\vec{p}_T^{\,\rm jet}||^2} = 1$. The PFF is not involved in the description of this reaction. The PFF manifests itself, for instance, in the subprocess reaction $gq \to gq$ followed by the gluon ($g \to \gamma + X$) or the quark ($q \to \gamma + X$) collinear fragmentations described by the distributions $D_{\gamma/g}(z_\gamma, M_F^2)$ and $D_{\gamma/q}(z_\gamma, M_F^2)$, the large scale M_F^2 being of order $(p_T^\gamma)^2$. At leading order (LO) we have $z_\gamma \le 1$ and the cross section $d\sigma^{\rm frag}/dz_\gamma$ is directly proportional to the functions $D_{\gamma/a}(z_\gamma, M_F^2)$ $(a = q,\ g)$. Therefore at leading order the total cross section $d\sigma/dz_\gamma$ is given by the sum of the direct contribution (proportional to $\delta(1 - z_\gamma)$) and of the fragmentation contribution containing the PFF $D_{\gamma/a}(z_\gamma, M_F^2)$. Contrarily to e^+e^- experiments we have to include a direct contribution in the cross section and stay away from $z_\gamma = 1$ to increase the sensitivity to the PFF.

When higher order (HO) corrections are taken into account, more jets can be present in the final state and z_γ may be larger than 1. With three partons in the final state, z_γ can be different from one also in the direct contribution.

The variable z_γ depends on the two transverse momenta $\vec{p}_T^{\,\gamma}$ and $\vec{p}_T^{\,\rm jet}$, none of them being *a priori* fixed for a given value of z_γ. However, $p_T^{\rm jet}$ is directly related (at least at LO) to the parton momentum involved in the hard subprocess. Therefore, if we vary $p_T^{\rm jet}$ to obtain different values of z_γ (keeping p_T^γ fixed), the theoretical cross section $d\sigma/dz_\gamma$ will reflect the z_γ dependence of $D_{\gamma/a}(z_\gamma, M_F^2)$ *and* the $p_T^{\rm jet}$ dependence of the subprocess, thus blurring the z_γ dependence of the PFF. On the contrary, if we keep $p_T^{\rm jet}$ fixed and vary p_T^γ, we obtain a z_γ dependence of $d\sigma/dz_\gamma$ coming dominantly from the fragmentation function. Therefore we propose to measure the PFF in experiments in which the jet momentum is kept fixed and the photon momentum is varied.

Let us finally note that the observed photon must not be isolated, which would considerably reduce the fragmentation contribution. This possibility exists when the photon p_T is not too large, as is the case at RHIC for $p_T^\gamma \lesssim 16$ GeV [10,36–38]. Therefore we choose the photon and jet momenta in agreement with the experiment performed at RHIC, i.e. in our numerical analysis we use $3 \le p_T^\gamma \le 16$ GeV, $11\ {\rm GeV} \le p_T^{\rm jet} \le 13$ GeV, and $\sqrt{s} = 200$ GeV. For the rapidities we take $-\frac{1}{2} \le y^\gamma \le \frac{1}{2}$ and $-1 \le y^{\rm jet} \le 1$. We use the CTEQ6M parton distribution functions [39] and renormalization and factorization scales given by $C \cdot p_T^{\rm jet}$ with $\frac{1}{2} \le C \le 2$.

[5] The PFF are from BFG set II [27]. Because of the D0 isolation requirement—less than 2 GeV of accompanying hadronic transverse energy in a cone of radius 0.4 in azimuth and rapidity around the photon direction—the prediction depends only marginally on the PFF choice.

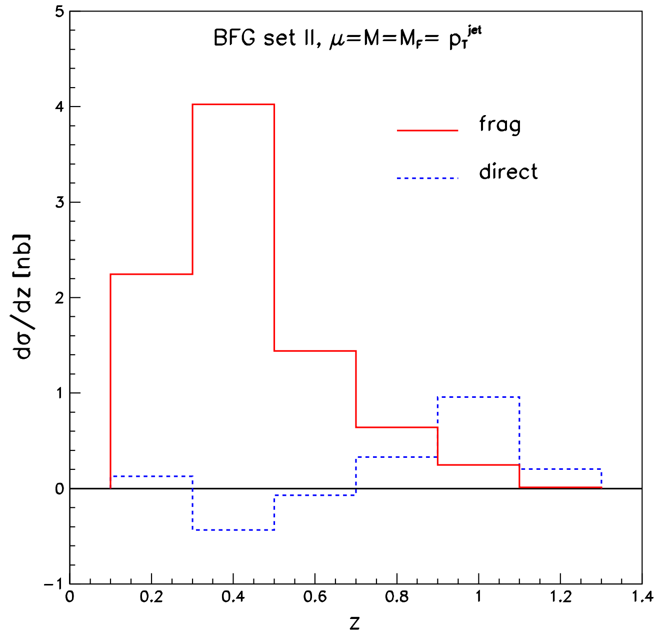

FIG. 4 (color online). Cross section $d\sigma/dz_\gamma$ for the BFG set II.

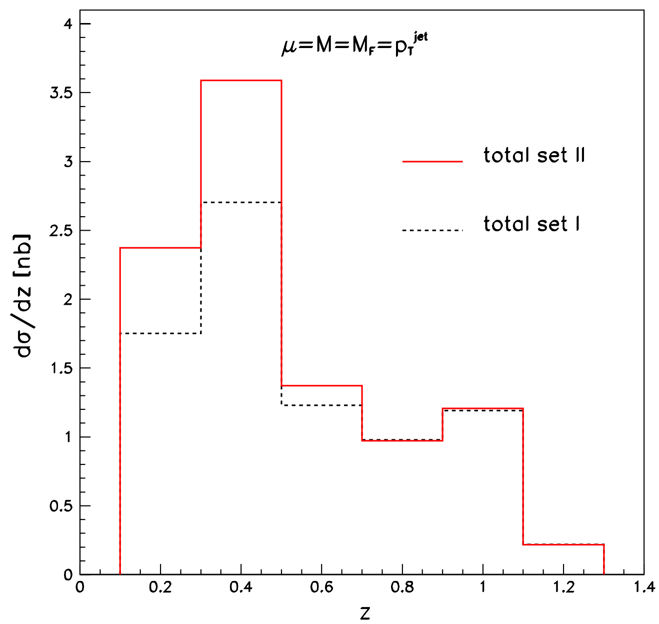

FIG. 5 (color online). $d\sigma/dz_\gamma$ for the two BFG sets I and II.

Discussion of numerical results

In Fig. 4 we present the results for the cross section $d\sigma/dz_\gamma$, calculated with the scales $\mu = M = M_F = p_T^{\rm jet}$ and the set II of the BFG fragmentation functions [27].

The jet is defined by the midpoint algorithm [16] with $R_{\rm cone} = 0.7$. We observe that at small values of z_γ, the fragmentation contribution is much larger than the direct one. Although at next-to-leading order, the fragmentation and direct contributions cannot be considered as independent physical channels, this feature persists for other scale choices. Therefore the photon fragmentation functions should be measurable in RHIC experiments at small values of z_γ, a region which was not accessible to LEP experiments.

In Fig. 5 we compare the predictions obtained with the sets I and II of the BFG fragmentation functions. The gluon fragmentation function of set I is smaller than the one of set II at small z_γ, leading to a significant difference in the $d\sigma/dz_\gamma$ distribution, as can be seen from Fig. 5. This result shows the sensitivity of this reaction to the photon fragmentation functions.

We find that the scale dependence at NLO is about $\pm 20\%$ as can be seen from Fig. 6. There are three scales involved: the renormalization scale μ, the initial state factorization scale M (we set the factorization scales for both initial state particles equal to M), and the final state factorization scale M_F. The dependence of the cross section on these scales is quite different.

In Fig. 6 we vary all three scales simultaneously. If we vary the final state factorization scale M_F only, keeping $\mu = M$ fixed, the fragmentation component increases logarithmically with M_F, while the direct contribution decreases, such that the leading logarithmic dependence cancels in the sum and the overall dependence on M_F is rather weak. We also checked that the dependence on the initial state factorization scale is very weak, such that the overall scale uncertainty is dominated by the renormalization scale dependence. This is demonstrated in Fig. 7, where we vary the renormalization scale μ only, keeping $M = M_F$ fixed to $p_T^{\rm jet}$. However, we can find a region where the cross section is more stable against variations

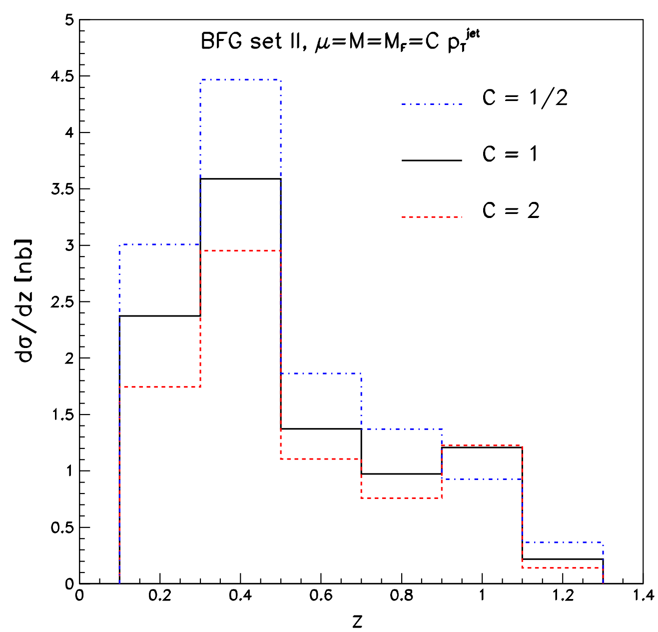

FIG. 6 (color online). Scale dependence of $d\sigma/dz_\gamma$ for a common variation of scale $\mu = M = M_F$.

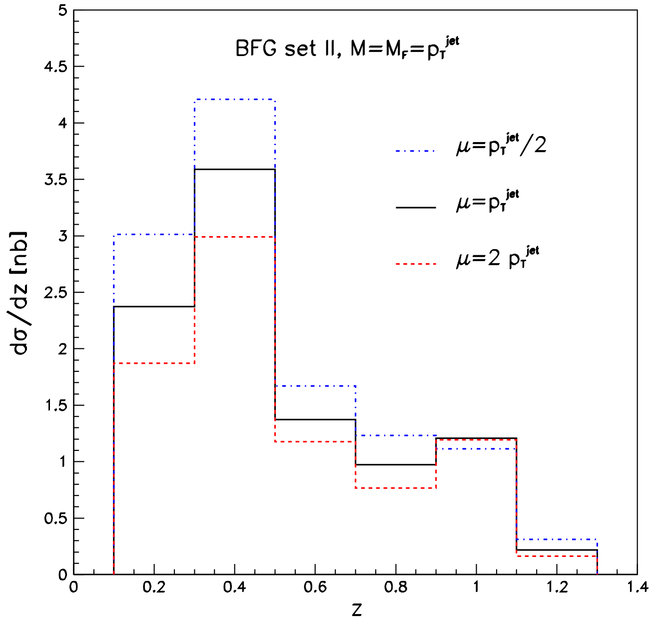

FIG. 7 (color online). Separate renormalization scale (μ) dependence of $d\sigma/dz_\gamma$ for fixed common factorization scales $M = M_F = p_T^{\rm jet}$.

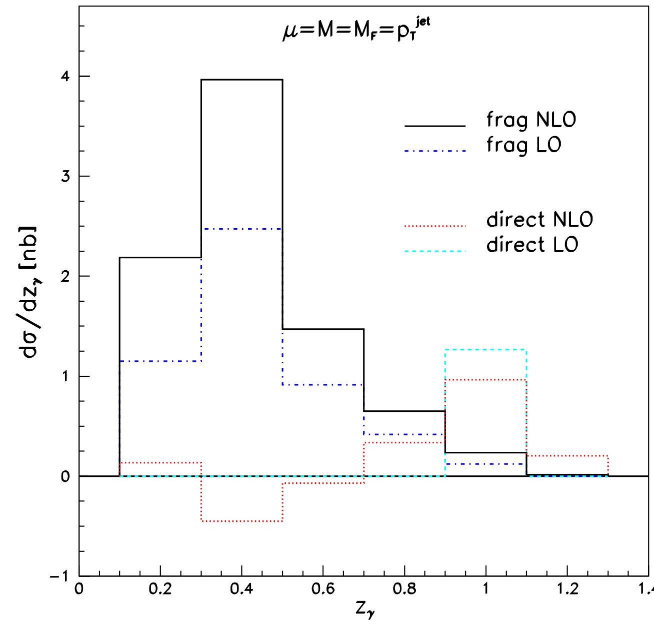

FIG. 9 (color online). Respective sizes of HO corrections in fragmentation and direct components for a given common scale choice.

of μ, which is in the vicinity of $M = M_F = p_T^{\rm jet}/2$ and $p_T^{\rm jet}/4 < \mu < p_T^{\rm jet}/2$, as can be seen from Fig. 8. This optimal behavior is obtained in the small-z domain in which the fragmentation contribution is large. We expect a similar behavior with the BFG set I of PFF since the sensitivity to the renormalization scale μ is mainly related to HO corrections involving the subprocess only, regardless of the PFF profile.

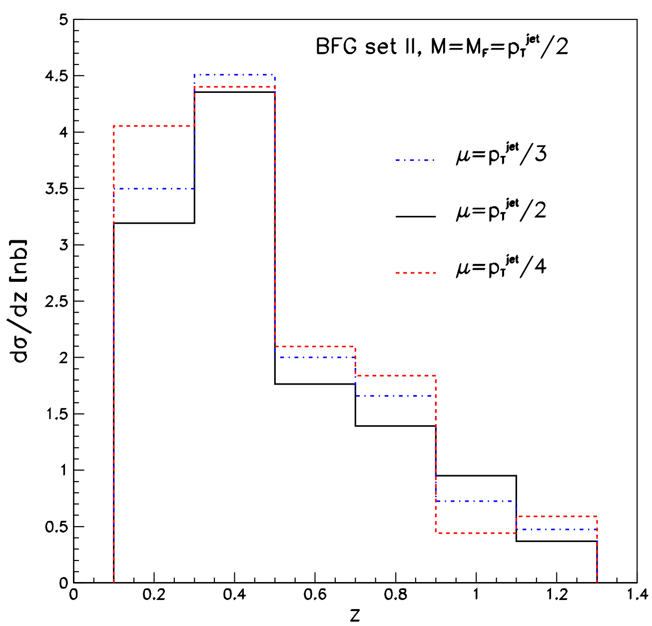

FIG. 8 (color online). Region of larger stability w.r.t. renormalization scale dependence.

Figure 9 shows that the size of the higher order corrections is much larger for the fragmentation component than for the direct component.

V. CONCLUSIONS

In this article we have studied photon-jet correlations in hadronic collisions based on the NLO program JETPHOX, which is a Monte Carlo program of partonic event generator type which incorporates NLO corrections to both direct photons and photons from fragmentation. The program is flexible to account for user-defined kinematic cuts and photon isolation parameters. It is available at the following web site: [13]. Correlation observables offer in general a larger sensitivity to the short distance dynamics than one-particle inclusive observables. We studied the photon-jet angular distribution $\cos\theta^*$ and the jet rapidity distribution in view of possible constraints on the parton distribution functions in the proton, in particular, the gluon.

Furthermore, correlations involving unisolated photons such as the ones measured at RHIC provide a means to constrain the photon fragmentation function in a region which was barely accessible by the LEP experiments. We study the observable $d\sigma/dz_\gamma$, where z_γ can be reconstructed from the photon and jet transverse momenta. We argue that the z_γ dependence of $d\sigma/dz_\gamma$ is coming dominantly from the fragmentation if we keep $p_T^{\rm jet}$ fixed and vary p_T^γ, and therefore propose to measure the fragmentation functions at fixed $p_T^{\rm jet}$. The NLO predictions still have a non-negligible dependence on the renormalization scale choice, which is related to the fact that the higher order corrections to the fragmentation component are large, exceeding 40%.

The program JETPHOX can also predict the tail of the distribution of transverse momentum Q_T of photon + jet pairs at NLO accuracy for large enough Q_T for the LHC, as well as any other correlations insensitive to multiple soft gluon emission, it thus can also help to normalize the Monte Carlo event generators suited to describe the lower Q_T range of the distribution of transverse momentum of photon + jet pairs and other less inclusive observables.

Note added.—While we were completing the present article, we became aware of a work by Stavreva and Owens [40], similar to the one reported here, but focusing on charm and bottom jets in the final state.

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