Prompt photon plus charm quark production at $p\bar{p}$ colliders

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We present a theoretical study of prompt photon plus charm quark production at the Fermilab Tevatron, comparing the results for two conceivable production mechanisms, which assume "massless" charmed partons in the proton, or massive charm quarks being produced extrinsically in pairs, respectively. We find that the two mechanisms yield very similar predictions and can well account for recent experimental results for the cross section.

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I. INTRODUCTION

The production of high-p_T^γ prompt photons in $p\bar{p}$ collisions provides invaluable information on the gluon distribution $g(x,\mu^2)$ of the proton due to the dominance of the leading order (LO) Compton-like $O(\alpha\alpha_s)$ subprocess $gq \to \gamma q$ over a wide kinematical range. Moreover, with improved statistics the experimental selection of final states containing a charm quark in association with the isolated prompt photon is achievable [1] by tagging on charmed D mesons or semileptonic decays of the charm quark [1].

At first glance this would be a direct probe of the "massless" charm sea quark content of the proton via the $gc \to \gamma c$ subprocess [2]. At low energies, however, one expects the $2 \to 3$ subprocesses $gg \to \gamma c\bar{c}$ and $q\bar{q} \to \gamma c\bar{c}$ with *massive* charm quarks [see Fig. 1(a)] to provide the correct LO $[O(\alpha\alpha_s^2)]$ theoretical description of prompt photon plus charm production, since they correctly take into account the threshold behavior of the cross section at $\hat{s} = \hat{s}_{\rm thr} \sim m_c^2$. As energy increases, possibly large logarithms $\sim \ln(m_c^2/\hat{s})$, stemming from almost collinear splittings $g \to c\bar{c}$ of an initial state gluon [Fig. 1(b)] as well as from small-angle photon radiation in $c \to \gamma c$ in the final state [Fig. 1(c)], appear in these subprocess cross sections. The question arises of whether it is necessary to resum these logarithms by introducing an intrinsic (massless) charm quark distribution of the (anti)proton and a charm-to-photon fragmentation function, each of them obeying a (LO) evolution equation. The complete LO $[O(\alpha\alpha_s)]$ description would then be given by the processes depicted in Figs. 1(d)–1(g): Figure 1(d) effectively resums the logarithms appearing in Fig. 1(b), whereas Fig. 1(e) corresponds to Fig. 1(d), the final state logarithms taken care of by the introduction of a fragmentation function. In what follows we will refer to the latter approach involving resummation of logarithms as the "massless" calculation, whereas the mechanism assuming that charm quarks can only be extrinsically produced as massive particles in pairs will be called "massive."

The massive and the massless approaches are different descriptions of the same process. The question of resumming logarithms when going far above the subprocess threshold ($\hat{s} \gg \hat{s}_{\rm thr} \sim m_c^2$) is closely linked with the perturbative stability of the massive approach. Clearly, if the logarithms appearing in the massive calculation spoil the perturbative expansion above some $\hat{s} \gg \hat{s}_{\rm thr}$, it is then necessary to resum these, following, e.g., the procedure described in [3] which mediates between the massive (providing the correct threshold behavior at $\hat{s} = \hat{s}_{\rm thr} \sim m_c^2$) and the completely massless

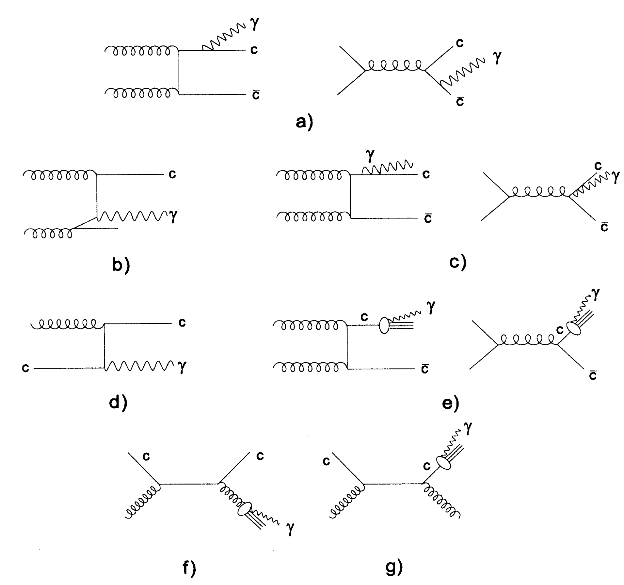

FIG. 1. LO Feynman diagrams for prompt photon plus charm quark production: (a) Diagrams for the "massive" calculation, (b) and (c) examples for almost collinear configurations in the initial or final state, (d) "direct" Compton-like contribution to the "massless" calculation, and (e)–(g) examples for fragmentation contributions to the "massless" calculation.

(asymptotic, $\hat{s} \gg \hat{s}_{\rm thr}$) approach, in order to achieve a better perturbative stability and consequently a more reliable theoretical description. But on the other hand, according to the results of [4], several processes in electro- and hadroproduction of heavy flavors, in particular heavy quark contributions to deep-inelastic structure functions and total hadroproduction cross sections, show perturbative stability in the framework of the massive calculation even at high energies ($\hat{s} \gg \hat{s}_{\rm thr}$). Here it was shown [4] that the appearance of the logarithms $\ln m_c^2/\hat{s}$ in the *partonic*, i.e., *non*observable, subprocess cross sections far above the subprocess threshold ($\hat{s} \gg \hat{s}_{\rm thr} \sim m_c^2$) is not necessarily dangerous for the perturbative stability of the experimentally observable quantities. Moderate K factors are obtained whenever the calculations are performed in a theoretically consistent manner, i.e., employing LO (next-to-leading order (NLO)] parton distributions and strong coupling constant values in conjunction with LO (NLO) subprocess cross sections. Consequently this would favor the use of the massive description not only at energies sufficiently close to the subprocess threshold ($\hat{s} \sim \hat{s}_{\rm thr}$) but even at high energies [4]. In this case a resummation of asymptotically large logarithms by introducing intrinsic massless heavy partons in the nucleon [3] might not represent a reliable theoretical description at presently achievable energies. Unfortunately, in the case of prompt photon plus charm production no NLO results are available yet, as we will discuss in more detail below. This makes it impossible to study the perturbative stability of the calculations. It is therefore interesting to at least examine to what extent the observed production rate for prompt photon plus charm events [1] can be explained by either assuming the presence of massless charmed sea quarks in the proton or by a massive charm treatment, and what kind of predictions are obtained for other observables in $p\bar{p} \to \gamma c X$.

Differences in the theoretical results for the massive and the massless approaches will then represent part of the theoretical uncertainties in our present understanding of the process $p\bar{p} \to \gamma c X$ at colliders.

Since the charm contribution to the *inclusive* isolated prompt photon production rates $p\bar{p} \to \gamma X$ is known to be non-negligible [$O(15$–$20\,\%)$] due to its large charge factor $e_c^2 = 4/9$ it is furthermore important to study to what extent a recent analysis [5] of the Collider Detector at Fermilab (CDF) prompt photon data [6], which removes previous discrepancies between theory and data at small $p_T^\gamma/\sqrt{S}$ within the fully massless framework, is affected by a massive charm treatment. The investigation of these questions is the subject of this work.

II. THEORETICAL BACKGROUND

The process we want to investigate is $p\bar{p} \to \gamma c X$ at CDF ($\sqrt{S} = 1.8$ TeV) [1], where the c stands for *any* observed charm activity in the prompt photon event, either stemming from charm quarks or from their antiquarks. As explained in the Introduction, we want to compare the predictions obtained by assuming that charm quarks can only be *extrinsically* produced as *massive* particles in pairs via interactions of the hadrons' *light* (massless) partons, i.e., u, d, s quarks and gluons g, with those taking into account the charm quark as a *massless* intrinsic parton of the (anti)proton.

In the *massive* calculation, photon plus charm events are generated in LO by the $2 \to 3$ processes $gg \to \gamma c\bar{c}$, $q\bar{q} \to \gamma c\bar{c}$ [see Fig. 1(a)] which are $O(\alpha\alpha_s^2)$. Our results for the corresponding spin-averaged matrix elements $|\overline{M}|^2$ agree with those published in [7] after crossing. The total cross section for producing a prompt photon with transverse momentum p_T^γ larger than a certain $p_{T,\rm min}^\gamma$ in a charmed event is then given by

$$\sigma^{p\bar{p}\to\gamma c X} = \sum_{a,b} \frac{1}{2^6\pi^4} \int_{p_{T,\rm min}^\gamma}^{\sqrt{S}\tilde{\beta}^2/2} \frac{dp_T^\gamma}{(p_T^\gamma)^3} \int_{-\eta_{\rm max}^\gamma}^{\eta_{\rm max}^\gamma} d\eta^\gamma \int_{\frac{(1-V)VW+4m_c^2/S}{(1-V)+4m_c^2/S}}^{V} dv \int_{VW/v}^{1/\left[1+4m_c^2(1-v)/(p_T^\gamma)^2\right]} dw$$
$$\times \int_0^\pi d\theta_c d\phi_c \; x_1 f_a(x_1,\mu^2)\; x_2 f_b(x_2,\mu^2)\; \hat{s} v^2 w(1-v) \frac{E_c \beta \sin\theta_c}{|\frac{\xi}{\beta}+\zeta|} |\overline{M}|^2_{ab\to\gamma c\bar{c}} \,, \quad (1)$$

where the sum runs over the *light* constituents of the proton, i.e., $a, b = u, d, s, g$, with their distributions f_a, f_b. Note that the cross section does not produce any singularity since the charm quarks have been taken to be massive. Therefore no regularization is needed despite the fact that we deal with a $2 \to 3$ process. In Eq. (1) we have used the definitions

$$\eta_{\rm max}^\gamma = \min\left\{ \eta_{\rm expt\ cut}^\gamma = 0.9, \; \ln\left[\frac{1}{x_T}\left(\tilde{\beta}^2 + \sqrt{\tilde{\beta}^4 - x_T^2}\right)\right] \right\} ,$$
$$\tilde{\beta} = \sqrt{1 - \frac{4m_c^2}{S}}, \quad \beta = \sqrt{1 - m_c^2/E_c^2} \;,$$

$$VW = \frac{x_T}{2} e^{\eta^\gamma}, \quad 1 - V = \frac{x_T}{2} e^{-\eta^\gamma}, \quad x_T = \frac{2p_T^\gamma}{\sqrt{S}} \;,$$
$$x_1 = \frac{VW}{vw}, \quad x_2 = \frac{1-V}{1-v} \;,$$
$$\xi = -2E_\gamma\left(\sin\theta_\gamma \sin\theta_c \cos\phi_c + \cos\theta_\gamma \cos\theta_c\right) + (x_1 - x_2)\sqrt{S}\cos\theta_c \;,$$
$$\zeta = 2E_\gamma - (x_1 + x_2)\sqrt{S} \;,$$
$$E_\gamma = p_T^\gamma \cosh\eta^\gamma, \quad \cos\theta_\gamma = \tanh\eta^\gamma \;,$$
$$\hat{s} = \frac{(p_T^\gamma)^2}{vw(1-v)} = x_1 x_2 S \;, \quad (2)$$

with η^γ and m_c denoting the rapidity of the prompt photon and the mass of the charm quark, respectively. It should be noted that the CDF experiment uses an isolation cut on the prompt photon [6, 1], which is defined by the requirement that the hadronic energy, accompanying the photon in a cone of opening angle $R = 0.7$, is bounded by a certain small fraction ϵ of the photon's energy. In terms of our variables this is expressed by

$$E_c \leq \epsilon E_\gamma \ , \quad \text{if} \quad \sqrt{(\eta^c - \eta^\gamma)^2 + \phi_c^2} \leq R \ , \tag{3}$$

where E_c and $\eta^c = -\ln\tan(\theta_c/2)$ are the energy and pseudorapidity of the charm quark [8], and $\epsilon = 2\ \text{GeV}/E_\gamma$ [6]. The criterion (3) has to be additionally imposed on Eq. (1) in order to match the experimental definition of the cross section.

In the complete LO *massless* calculation of $p\bar{p} \to \gamma c X$, which is of order $O(\alpha\alpha_s)$, there are *two* types of contributions: namely the direct piece $cg \to \gamma c$ [see Fig. 1(d)] which obviously depends on the intrinsic charm distribution in the (anti)proton, and the fragmentation contribution [Figs. 1(e)–1(g)] which is also of $O(\alpha\alpha_s)$ because the LO fragmentation functions are of $O(\alpha/\alpha_s)$. The (direct) quark-antiquark annihilation process $c\bar{c} \to \gamma g$ does not contribute here since it does not lead to a charmed final state. For the LO fragmentation contribution, the photon is produced by fragmentation of a final state parton in any $2 \to 2$ QCD process which contains a charmed particle (c and/or $\bar{c}$) in the final state, e.g., $q\bar{q} \to c\bar{c}$, $cg \to cg$, etc., via the $O(\alpha/\alpha_s)$ fragmentation function $D_i^\gamma(z, \mu_F^2)$ ($i = q, g$) at scale μ_F. The fragmenting particle can either be a noncharmed particle, which requires that an intrinsic charm quark of the (anti)proton takes part in the process [Fig. 1(f)], or a charm particle [Fig. 1(g)] which can also be produced in the final state [Fig. 1(e)]. We take into account all these contributions, in particular, we assume that the fragmentation remnant X in the fragmentation process $c \to \gamma X$ or $\bar{c} \to \gamma X$ still contains charm.

The relevant expressions for the cross sections in the direct and the fragmentation cases can be found, e.g., in detail in Ref. [9] and need not be repeated here. As explained in Refs. [10, 11], the experimental isolation criterion (3) is imposed on the massless (LO) cross section by restricting the fragmentation variable z appearing in the parton-to-photon fragmentation function $D_i^\gamma(z, \mu_F^2)$ to

$$z \geq \frac{1}{1+\epsilon} \ , \tag{4}$$

with the experimental energy resolution parameter ϵ introduced in Eq. (3). Furthermore, the fragmentation scale μ_F should be chosen of order $\mu_F \sim R p_T^\gamma$ [10], where R is the opening of the isolation cone.

Before presenting results for the massive and the massless prompt photon plus charm cross sections, let us briefly discuss the question of NLO corrections. For the massive case, these would require knowledge of $2 \to 4$ contributions such as, e.g., $gg \to \gamma c\bar{c}g$, and of the virtual corrections to the leading order ($2 \to 3$) graphs. All these contributions are completely unknown and their calculation is far beyond the scope of this work. In the massless case, the fully inclusive cross section $p\bar{p} \to \gamma X$ (i.e., without demanding charm in the final state) can be calculated to NLO [$O(\alpha\alpha_s^2)$] using the results of [12, 13, 9] for the direct contributions $ab \to \gamma cd$ and the ones of [14] for the NLO fragmentation contribution. Furthermore, it has recently been shown in [11] how the experimental isolation constraints can be consistently implemented into the calculation of the cross section beyond the LO, in this way removing [5] previous discrepancies between theoretical results and experimental collider data [6, 15] for isolated inclusive prompt photon production at small $p_T^\gamma/\sqrt{S}$.

For our present purpose, however, these NLO results cannot be used. The reason is that in a completely massless calculation the invariant mass squared of the produced $c\bar{c}$ pair in, e.g., the NLO direct process $c\bar{c} \to \gamma c\bar{c}$ can vanish *if* the final state charm quarks are completely integrated over their phase space as is the case for the results in [12, 11, 14]. This feature leads to uncanceled pole contributions in the result [16]. These singularities can only be avoided by either introducing suitable cuts on the invariant mass, or by fixing the kinematical variables p_T^c, η^c of one of the charm quarks. The latter calculation would require knowledge of the inclusive isolated prompt photon plus charm particle NLO cross section (direct as well as fragmentation contribution) in which the charm quark has *not* been integrated over its full phase space. This cross section is unknown so far.

For these reasons we have to stick to LO results for our calculations of massive and massless photon plus charm production, which in any case should be sufficient for our purpose to compare the two mechanisms. For all our numerical results presented in the next section K factors of order 40% or less, as known from inclusive prompt photon production $p\bar{p} \to \gamma X$ [9, 11], should be expected. For the massive calculation, the latter statement is a mere assumption. As mentioned in the Introduction, it is desirable in view of potentially large logarithms $\sim \ln(m_c^2/\hat{s})$, which appear in the calculation, that this assumption is checked in the future, i.e., that the perturbative stability of the massive calculation is proven as it was recently achieved for the case of the charm contribution to the proton's structure functions $F_{2,L}(x, Q^2)$ as well as for total hadronic heavy flavor production cross sections [4]. As long as the perturbative stability of the massive calculation for $p\bar{p} \to \gamma c X$ is an open question, any difference between the two conceivable production mechanisms gives an estimate of a part of the theoretical uncertainties involved in such a calculation.

III. RESULTS AND DISCUSSION

To begin with, we specify our choice for the input distributions and parameters. For the LO parton distributions which we need for a consistent LO calculation we will generally use those of Glück, Reya, and Vogt (GRV) [17], and the CTEQ2L set [18] for comparison [19]. Both parametrizations provide intrinsic masslessly evolved charm distributions, which we can use in the massless calculation. We employ the Λ_{QCD} values corresponding to the respective parton distributions in the LO expression for α_s. For the scales in the parton distributions and α_s we use, unless stated otherwise, $\mu = p_T^\gamma/2$, which was the preferred scale in the phenomenological analysis of the CDF data on inclusive prompt photon production [5]. For the fragmentation part of the massless calculation we use the LO set of the GRV parton-to-photon fragmentation functions [20] (which also provides a charm-to-photon fragmentation function) with the fragmentation scale $\mu_F = Rp_T^\gamma$, where $R = 0.7$ [6]. Finally, our value for the charm quark mass is $m_c = 1.5$ GeV.

In Table I we compare our results for the completely integrated cross section ($p_T^\gamma \geq p_{T,\min}^\gamma = 16$ GeV, $|\eta^\gamma| \leq 0.9$) for $p\bar{p} \to \gamma c X$ at CDF ($\sqrt{S} = 1.8$ TeV) obtained with the two available sets of LO parton distributions and for two different choices of scales. These results can, after division by 2, be directly compared to the experimental value [1], where (charm + anticharm events)/2 have been measured:

$$\sigma(p\bar{p} \to \gamma c X) = 665 \pm 314(\text{stat}) \pm 173(\text{syst}) \text{ pb} \quad . \tag{5}$$

As can be seen from Table I, the massive as well as the massless calculation can, in view of the large experimental error and the theoretical uncertainties such as NLO corrections and the choice of scales and parton distributions, equally well account for the experimental finding. In particular, the nonzero experimental result is *not* necessarily to be interpreted as a signature for an intrinsic charm distribution of the proton. It should be noted that a variation of the charm quark mass, e.g., from $m_c = 1.5$ to 1.3 GeV, does not alter our massive results significantly [$O(10\%)$].

Assuming that experimental statistics can be further improved [1], it is interesting to study differential cross sections for prompt photon plus charm production. For this purpose we show in Fig. 2(a) the cross section differential in the photon's transverse momentum p_T^γ with the rapidity η^γ being integrated over $|\eta^\gamma| < 0.9$. As in Table I we choose two different scales in order to get an

TABLE I. Results for the completely integrated ($p_T^\gamma > p_{T,\min}^\gamma = 16$ GeV, $|\eta^\gamma| \leq 0.9$) cross section for $p\bar{p} \to \gamma c X$ at $\sqrt{S} = 1.8$ TeV within the "massive" [Eq. (1)] as well as the "massless" framework for two different scales μ and two sets of LO parton distributions [GRV (LO) [17] and CTEQ2L [18]].

$\sigma^{p\bar{p}\to\gamma cX}$ (pb), $p_T^\gamma > p_{T,\min}^\gamma = 16$ GeV, $\lvert\eta^\gamma\rvert \leq 0.9$				
Scale μ	GRV (LO)		CTEQ2L	
	Massive	Massless	Massive	Massless
p_T	732.5	1026.4	728.6	879.5
$p_T/2$	1006.0	1005.1	924.3	787.3

estimate of the scale dependence of our calculations. It can be seen that the results for the two mechanisms are again very similar, in particular for the scale $\mu = p_T^\gamma/2$. Figure 2(b) shows the corresponding results for the distribution in the photon's rapidity, η^γ, at $p_T^\gamma = 10$ and 20 GeV and for $\mu = p_T^\gamma/2$.

It is furthermore interesting to examine distributions differential in charm variables, such as the rapidity η^c. The latter distribution is shown in Fig. 3, where again the photon's rapidity has been integrated over $|\eta^\gamma| \leq 0.9$. The difference in the results for the massive and the massless calculations turns out to be stronger than before.

Finally we examine the question whether the CDF data [6] for inclusive isolated prompt photon production, $p\bar{p} \to \gamma X$, which could recently be theoretically reproduced in the massless calculation [5], can be equally well described in the framework of the massive calculation. This question is interesting in view of the fact that massless charm contributes $\sim$ 15–20 % to the results of [5] due to its large charge and thus played a non-negligible role in the calculation of [5] when previous discrepancies between theory and data at small p_T^γ were removed. In order to include the massive charm contribution instead of the massless one, we add it to the result for inclusive iso-

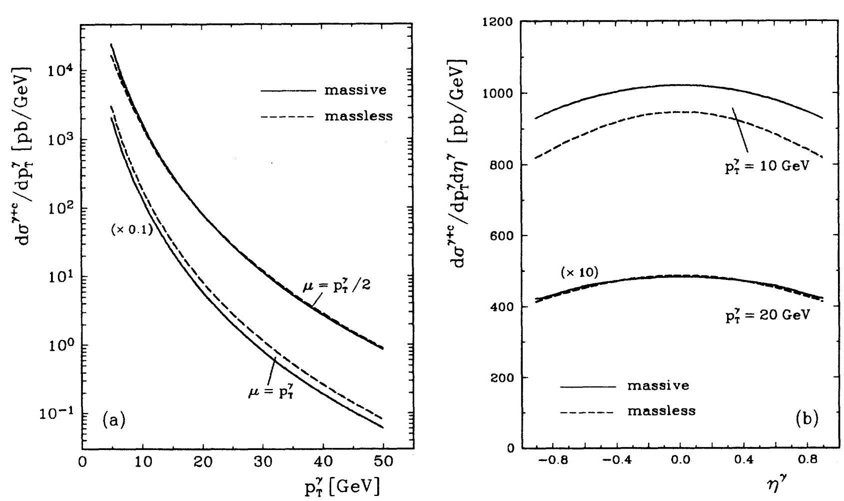

FIG. 2. (a) The prompt photon plus charm quark cross section at the Tevatron ($\sqrt{S} = 1.8$ TeV) as a function of p_T^γ, integrated over $|\eta^\gamma| \leq 0.9$ for two different scales in the "massive" and the "massless" case, using the GRV parton distributions [17] and the GRV fragmentation functions [20] for the "massless" calculation. The results for the scale $\mu = p_T^\gamma$ have been divided by 10 in order to allow for a better distinction of the curves. (b) Same as in (a), but as a function of η^γ for fixed values of p_T^γ and the scale $\mu = p_T^\gamma/2$. The results for $p_T^\gamma = 20$ GeV have been multiplied by 10.

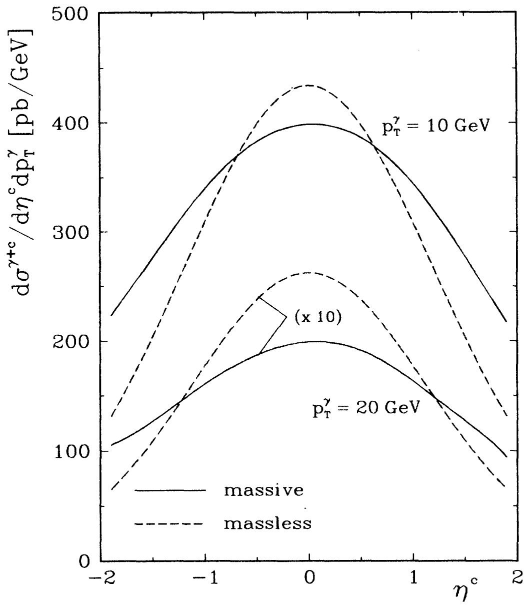

FIG. 3. Same as in Fig. 2(b), but as function of the charm quark rapidity η^c and integrated over $|\eta^\gamma| \leq 0.9$.

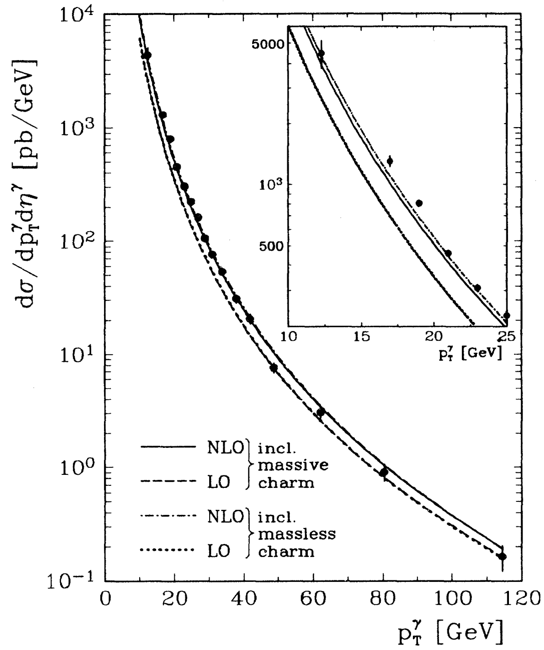

FIG. 4. LO and NLO inclusive prompt photon cross section $d\sigma^{p\bar{p}\to\gamma X}$ for the "massive" calculation, according to Eq. (6) (see text), compared to the results for the completely "massless" calculation, taken from Ref. [5]. The data points have been taken from Ref. [6].

lated prompt photon production obtained by using only $f = 3$ light flavors ($d\sigma_{f=3}^{p\bar{p}\to\gamma X}$):

$$d\sigma_{\text{massive}}^{p\bar{p}\to\gamma X} = d\sigma_{f=3}^{p\bar{p}\to\gamma X} + d\sigma_{\text{mass charm}}^{p\bar{p}\to\gamma X} \quad . \tag{6}$$

Strictly speaking, this is only consistent in LO, since the massive charm contribution to inclusive prompt photon production, $d\sigma_{\text{mass charm}}^{p\bar{p}\to\gamma X}$ [cf. Eq. (1)], is available only in LO as discussed in Sec. II. Nevertheless, in order to obtain an estimate for the NLO inclusive prompt photon cross section including massive charm, we also use the NLO $f = 3$ cross section in Eq. (6). The corresponding results are shown in Fig. 4, where the scale $\mu = p_T^\gamma/2$ has been chosen. For comparison we also show the results of Ref. [5] which were obtained assuming $f = 4$ light flavors. As could be expected from the previous results [Fig. 2(a)], there is again no sizable difference between the massive and the massless results, and both describe the data equally well also in the notorious region of small $p_T^\gamma/\sqrt{S}$ (see inset in Fig. 4).

To conclude, we have shown that a calculation assuming massive charm quarks being produced in the final state by $gg \to \gamma c\bar{c}$, $q\bar{q} \to \gamma c\bar{c}$, and a calculation using a distribution of masslessly evolved charm quarks in the proton and a charm-to-photon fragmentation function give very similar results for photon plus charm production at the Fermilab Tevatron. Thus the observation of such events does not necessarily point towards the existence of an intrinsic massless charm distribution. In other words, the approximate equality of massive and massless results might indicate that the effects of resummation of potentially large logarithms, which takes place in a QCD evolved LO intrinsic charm distribution, are small at least at Fermilab Tevatron energies. However, as discussed in Sec. II, we have to emphasize the importance of checking the perturbative stability of the massive calculation in order to prove the latter presumption. At the level of the presented LO calculations the uncertainties induced by the theoretical approach to the issue of massive particles taking part in the reaction $p\bar{p} \to \gamma cX$ seem to be rather small compared to the other uncertainties involved in such calculations such as, e.g., the scale dependence of the results.

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